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AI, Metacognition, and Digital Literacy in Physics Education: Systematic Literature Review and Bibliometric Analysis

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ABSTRACT

Purpose – This study critically examines the rapid expansion of artificial intelligence (AI) in digital learning, with a specific focus on how these technologies intersect with metacognitive skills and digital literacy in science/STEM education. This study explicitly investigates their conceptual integration and identifies a substantiated research gap in physics learning contexts.

Methodology – A systematic literature review (SLR) combined with bibliometric analysis was conducted in accordance with the PRISMA 2020 protocol. Articles were retrieved from Scopus using structured TITLE-ABS-KEY queries and limited to peer-reviewed journal articles (2020–2025) within the Social Sciences domain. From 2,670 initial records, 47 articles met predefined inclusion criteria (n = 47). Bibliometric mapping was performed using VOSviewer, followed by thematic synthesis employing open, axial, and selective coding to analyze AI intervention types, pedagogical mechanisms, and measurement approaches for metacognition and digital/AI literacy.

Findings – Bibliometric evidence indicates a sharp rise in publications from 2023 onward, with education and educational technology channels dominating the dissemination landscape. Metadata screening further revealed an explicit research void regarding the integrated study of AI, metacognition, and digital literacy in physics learning. Thematic synthesis suggests AI can enable more personalized learning trajectories, richer formative feedback, and improved self-regulation supports that align with metacognitive development and digital literacy practices.

Contribution – This study provides a bibliometrically grounded knowledge map of AI–metacognition–digital literacy research and conceptual adaptation framework proposing physics-oriented AI learning design principles and task-based assessment directions to guide future empirical research.

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INTRODUCTION

Over the past decade, advances in digital technology and artificial intelligence (AI) have reshaped how people access, produce, and make meaning from information, including in science education. Deep learning–based AI is no longer merely a supportive tool; it has become part of a social infrastructure that mediates learning processes, decision-making, and participation as digital citizens (Reyes et al., 2025; Tiernan et al., 2023). In the global context, the integration of AI in education aligns with the Sustainable Development Agenda, particularly SDG 4, which emphasizes equitable access and improved educational quality. In classrooms, AI applications are rapidly expanding through intelligent tutoring systems, learning analytics, conversational agents (chatbots), AI e-books, and machine learning–based learning games that offer personalized learning pathways and real-time feedback (Xie et al., 2025; Zammit et al., 2022). Furthermore, the emergence of generative AI such as ChatGPT has accelerated AI adoption across educational levels while introducing new dynamics: opportunities to enhance motivation, collaboration, and academic performance, alongside risks such as plagiarism, bias, information reliability issues, and reduced deep cognitive engagement (Ibeh et al., 2025; Jwair, 2025).

Although the literature highlights the potential of AI and deep learning in learning, research that explicitly positions metacognitive skills as a primary outcome in science learning, especially within specific sub-disciplines such as physics, remains limited. Science and physics education continue to face persistent challenges: low conceptual understanding, difficulty connecting mathematical, visual, and verbal representations to phenomena, and weak problem-solving and self-reflection. However, metacognition, the ability to plan, monitor, and evaluate one's thinking processes, correlates with learning success in digital and STEM environments (Anthonysamy, 2023). At the same time, digital literacy and AI literacy are increasingly seen as prerequisites for learners to use AI critically and ethically; digital literacy has even been reported as an important mediator that determines whether metacognitive strategies translate into improved learning performance (Anthonysamy, 2023; Ng et al., 2024). However, measurements of metacognition and digital/AI literacy remain inconsistent: many studies rely on perceptions or self-reports and rarely link AI use to more objective changes in learners' abilities. Bibliometrically, the absence of articles that explicitly combine AI–deep learning, metacognition, digital literacy, and the context of physics learning further confirms a substantial research gap.

Despite the rapid expansion of AI applications in education, three intertwined gaps remain. First, most studies examine AI adoption, metacognition/self-regulated learning, or digital/AI literacy in isolation, leaving evidence on how these constructs interact within science learning designs fragmented. Second, outcome evidence is methodologically uneven; metacognition and literacy are frequently measured via self-report, with limited triangulation using trace data or task-based measures that capture planning, monitoring, and evaluation during problem solving (Craig et al., 2020; Kilgour et al., 2022). Third, physics is virtually absent at this intersection, even though physics learning uniquely requires multi-representational reasoning and quantitative sense-making (Edwards & Maree, 2025; Kokkonen & Schalk, 2021). These gaps constrain the field's ability to formulate robust design principles and assessment approaches for responsibly leveraging deep learning–based AI in physics learning.

To address this issue, the present study proposes a Systematic Literature Review (SLR) combined with bibliometric analysis to map the research landscape on deep learning–based AI integration in science learning at the intersection of metacognition and digital literacy. The SLR is used to select, code, and transparently synthesize findings across studies. At the same time, bibliometric analysis is used to identify publication trends, thematic clusters, keyword networks, and the field's intellectual structure. Because no studies explicitly situated in physics education were found in the corpus, physics is positioned as a research gap addressed through a cross-context adaptation framework: (1) identifying types of AI interventions (chatbots, intelligent tutors, learning analytics, generative AI, VR/immersive learning) and their pedagogical mechanisms; (2) mapping which indicators of metacognition and digital/AI literacy are measured and how instruments are validated; and (3) deriving learning design principles relevant to physics-specific characteristics (multiple representations, problem solving, and conceptual reflection), including activity designs such as reflective prompting, validation of AI outputs, and modeling of conceptual errors. Thus, the proposed solution does not force generalizations from physics studies that are not yet available; instead, it builds an evidence-based conceptual adaptation grounded in cross-context findings from science and STEM education.

The theoretical framework of this study is grounded in several foundations. First, metacognitive theory and self-regulated learning emphasize three core processes—planning, monitoring, and evaluation—which can be triggered through adaptive feedback and reflective dialogue with AI (Anthonysamy, 2023; Lozano & Fontao, 2023). Second, digital literacy and AI literacy are conceptualized as overarching competencies that include cognitive, social, and ethical dimensions in accessing, evaluating, and creating information; AI literacy adds an understanding of how AI works, its biases, and its ethical implications (Levy-Nadav et al., 2025). The ABCE framework (Affective, Behavioral, Cognitive, Ethical) reinforces a holistic view of successful AI integration as not only about technical skills but also about emotions, learning behaviors, cognitive processes, and ethics (Al-smadi et al., 2025; Ng et al., 2024). Third, a critical constructivist perspective emphasizes that AI's impact on metacognition is not automatic; learning designs must cultivate epistemic vigilance—habits of verifying, testing the reliability of AI outputs, and reflecting on conceptual reasoning—so that learners do not develop cognitive dependence (Haroud & Saqri, 2025; Muñoz et al., 2025). Fourth, in physics, multiple representation theory and problem-solving perspectives highlight the importance of linking mathematical models, visualizations, and conceptual narratives; AI can serve as a mediator to strengthen representational connections through simulations, multimodal explanations, and experimental data analysis that prompts reflection (Xie et al., 2025; Yang, 2022).

Prior studies share similarities with this research in recognizing AI as a means to strengthen learning personalization and adaptive feedback, and in positioning generative AI and chatbots as cognitive mediators that may support reflection and self-regulation (Muñoz et al., 2025; Zammit et al., 2022). Several studies also highlight digital/AI literacy as essential to ensure AI use remains critical, ethical, and does not widen educational inequities (Shoval, 2025). However, these studies generally differ from the present study in several respects: (1) many focus on language contexts, general literacy, or distance education rather than the distinctive demands of science and physics, which require multiple representations and layered problem solving; (2) metacognitive outcomes are often treated as secondary effects rather than primary targets and are frequently measured through perception-based indicators without triangulation using more objective measures; (3) instruments for digital/AI literacy and metacognition vary widely and are not always strongly validated for specific science contexts; and (4) the combined use of SLR and bibliometrics remains relatively rare for simultaneously identifying thematic clusters and deriving instructional design implications. The novelty of this study lies in a systematic SLR–bibliometric mapping that connects AI, deep learning, metacognition, and digital literacy, while explicitly establishing "physics learning" as a bibliometrically evidenced gap and addressing it through a cross-context conceptual adaptation framework. Accordingly, this study strengthens the novelty claim by integrating PRISMA-guided SLR with bibliometric mapping to reveal the field's intellectual structure and thematic clusters, quantify the physics void in the international corpus, and translate cross-context evidence into a physics-oriented adaptation framework. Beyond mapping trends, it synthesizes actionable design-and-measurement directions (intervention mechanisms, validated indicators, and task-based assessment options) that can be empirically tested in future physics classrooms.

Based on the above rationale, the objectives of this study are: (1) to map the characteristics of international publications on deep learning–based AI integration in science learning related to metacognition and digital literacy; (2) to identify forms of AI-supported learning interventions in science contexts and their potential adaptation for physics learning; (3) to examine the instruments/indicators used to measure metacognitive skills and digital literacy in selected studies; and (4) to formulate pedagogical implications for developing AI–deep learning–based science learning designs and directions for implementation in physics learning. In line with these objectives, the research questions are as follows:

1. What are the international publication trends related to deep learning–based AI integration in science

learning that targets metacognitive skills and digital literacy?

2. What forms of AI-assisted learning interventions are used in science contexts, and what is their potential for adaptation to physics learning?
3. What instruments are used to measure metacognitive skills and digital literacy in selected studies, and what is the potential for conceptual adaptation of these instruments to the context of physics learning?
4. What pedagogical implications can be derived from the literature for developing AI–deep learning–based science learning designs oriented toward strengthening metacognition and digital literacy, and what is the direction of their conceptual adaptation for physics learning?

This study makes three reinforced contributions. Scientifically, it provides an evidence-based bibliometric atlas (trends, core outlets, country networks, and keyword clusters) that delineates how deep learning–based AI, metacognition, and digital/AI literacy co-evolve in science/STEM education while pinpointing the physics-specific gap. Methodologically, it offers a replicable SLR–bibliometric synthesis workflow and a transparent coding scheme that links AI intervention types, pedagogical mechanisms, and measurement quality (including instrument validation and triangulation). Practically, it formulates physics-ready learning design principles and an adaptation agenda—reflective prompting, AI-output verification, multi-representational problem-solving supports, and ethics-by-design—providing a concrete roadmap for developing and evaluating AI-supported physics learning that strengthens metacognition and digital/AI literacy.

METHODOLOGY

Research Design

This study employs a systematic literature review (SLR) and bibliometric analysis. The SLR was selected to produce a rigorous, transparent, and replicable synthesis of evidence on the integration of deep learning–based AI in science learning (science education), with a focus on metacognitive skills and digital literacy. Bibliometric analysis is used to map publication trends, keyword networks, and the distribution of contributing countries and journal sources. The synthesized findings are then used to formulate pedagogical implications and directions for adaptation relevant to the development of physics learning. The unit of analysis is the journal article; therefore, the sample in this study refers to the final article corpus (n = 47).

This research is a systematic literature review designed using steps adapted from the PRISMA protocol, including identification, screening, eligibility assessment, and article inclusion. In parallel, a bibliometric analysis is conducted using bibliographic data from Scopus, processed with VOSviewer to generate visual maps of keyword networks and the geographical distribution of publication origins. To strengthen methodological clarity, a review protocol was specified before screening, detailing the research questions, search strategy, eligibility criteria, extraction variables, and synthesis procedures.

Data Sources, Subjects, and Context

The primary data source comprised peer-reviewed international journal articles indexed in Scopus. The search was conducted on 7 December 2025 using the query: TITLE-ABS-KEY (“Artificial Intelligence” OR “Deep Learning” OR “Physics Learning” OR “Metacognitive Skills”) AND TITLE-ABS-KEY (“Digital Literacy”), with deep learning included to ensure coverage of the technological foundations of contemporary educational AI despite the broader term artificial intelligence being used in the title. Although “Physics Learning” was incorporated to capture AI–deep learning integration in physics contexts, PRISMA screening and metadata examination (title, abstract, author keywords, and index keywords) revealed no articles explicitly indicating a physics education context; thus, physics learning is treated as a research gap and discussed through implications derived from science/STEM and general education findings, acknowledging that some relevant studies may not have explicitly labeled their context in metadata. The results were limited to publication years 2020–2025, subject area Social Sciences, document type article, final publication status (excluding articles in press), and relevant language and access criteria, and further refined to journals focusing on education and educational technology (e.g., Education Sciences, Frontiers in Education, Cogent Education, Computers and Education: Artificial Intelligence, Education and Information Technologies, and Digital Education Review). The initial search yielded 2,670 records, of which 47 articles met the inclusion criteria after applying the PRISMA 2020 stages (identification, screening, eligibility, and inclusion) and were subsequently analyzed bibliometrically and synthesized thematically.

Article Selection Procedure

The article selection process followed the PRISMA 2020 stages (identification, screening, eligibility assessment, and inclusion) using predefined criteria and documented reasons for exclusion at each stage. The number of articles at each stage is presented in Figure 1.

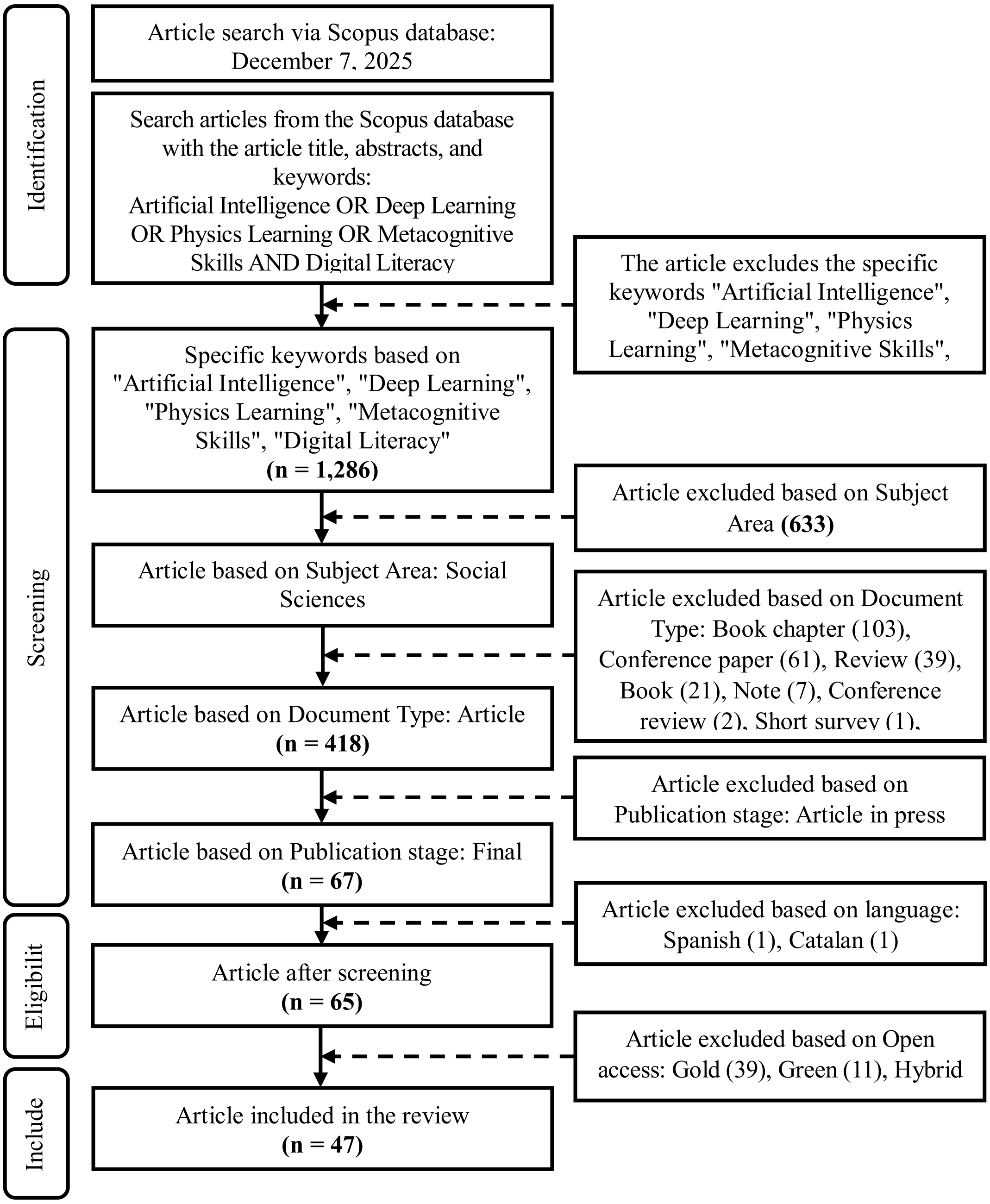


Figure 1. Article selection flowchart based on PRISMA 2020

The eligibility stage involved reading the abstracts and full texts to ensure relevance. Articles that did not provide sufficient information about learning interventions or the measurement of learners' skills were excluded. In the end, 47 articles met the criteria and were included in both the qualitative and bibliometric syntheses.

Review Instrument and Analysis Categories

The review instrument consisted of a data-extraction sheet developed to record the key information from each article, including: (1) publication identity (authors, year, journal, country); (2) research design (quantitative, qualitative, mixed methods, conceptual); (3) contextual information (educational level and subject area, including whether the study was directly related to physics/science); (4) the type of AI used (e.g., intelligent tutoring systems, chatbots, generative AI, AI e-books, adaptive systems using machine learning, deep learning–based analytics); (5) learning outcome focus (metacognition, digital literacy, AI literacy, self-regulated learning, computational thinking, and other cognitive outcomes); and (6) the measurement instruments or indicators used.

To ensure transparency and replicability, the extraction sheet was operationalized as a coding form supported by a codebook (variable definitions, coding rules, and allowable values). The form was pilot-tested on a subset of articles and refined before full extraction. Instrument-related fields recorded for each study included: (a) construct(s) measured (metacognition, digital literacy/AI literacy, SRL, etc.); (b) instrument name/source (e.g., OSLQ/MSLQ-based scales; AILQ); (c) instrument type/format (self-report Likert, performance task, rubric/product assessment, log/trace analytics); (d) indicator coverage (key indicators or item domains); (e) measurement timing (pre–post, post-only, longitudinal); and (f) reported psychometric evidence (e.g., reliability/alpha; validity evidence if available). To reduce subjectivity, coding consistency was checked by re-reading abstracts/full texts when intervention–outcome links or measurement descriptions were unclear, and disagreements were resolved by applying the predefined codebook rules.

For metacognitive skills, the analysis categories referred to the dimensions of planning, monitoring, and regulation, as developed in the Online Self-Regulated Learning Questionnaire (OSLQ) and the Motivated Strategies for Learning Questionnaire (MSLQ), as adapted by Anthonysamy (2023). For digital literacy and AI literacy, the categories were guided by relevant frameworks and by the ABCE model (Affective, Behavioural, Cognitive, Ethical) within the AI Literacy Questionnaire (AILQ) developed by Ng et al. (2024) as well as extensions discussed by Tiernan et al. (2023) and Yim & Su (2025) regarding information–media literacy in the AI era. Operationally, metacognition was coded as evidence of measuring: (i) planning, (ii) monitoring, and (iii) regulating/evaluating. Digital literacy/AI literacy was coded as emphasizing: (i) technical–operational, (ii) cognitive–critical evaluation (verification of information/AI outputs, bias awareness), (iii) behavioral participation/responsible use, and (iv) ethics (privacy, integrity, societal impact) aligned to ABCE.

Adaptation Framework for Physics Learning (Derived from Cross-Context Findings)

This section proposes an adaptation framework for physics learning, derived from a thematic synthesis and a bibliometric mapping of the selected corpus. Because no studies were explicitly labeled as physics education in the Scopus metadata, the framework does not represent a direct generalization from physics-specific research but rather a transfer of cross-context evidence from general education and STEM/science education to the distinctive characteristics of physics learning. The synthesized findings indicate several potential forms of AI and deep learning integration, including intelligent tutoring systems with adaptive feedback, AI-supported interactive e-books, machine learning–based learning analytics to predict conceptual difficulties, conversational agents for problem-solving support, and AI-based educational games for abstract concepts (Xie et al., 2025; Zammit et al., 2022). Conceptually, the framework positions AI as a cognitive and metacognitive mediator that collects learning data, models students' knowledge states, and provides adaptive scaffolding and simulation-based exploration with data-driven feedback. This framework is intended as an initial pedagogical design guide for future empirical testing in physics education.

Data Analysis Techniques

Bibliometric analysis was conducted by processing Scopus CSV files to identify the distribution of articles by publication year, journal source, and country of origin, and to construct keyword network maps using VOSviewer. The bibliometric procedure followed a replicable workflow consisting of three stages. First, the dataset was cleaned by removing duplicate records, standardizing country and journal-source names, and merging synonymous keywords using a thesaurus file. Second, descriptive statistics were calculated to summarize the number and proportion of publications by year, journal source, and country or territory. Third, keyword network mapping was performed in VOSviewer. For keyword mapping, the analysis used all keywords, including both author keywords and indexed keywords, with full counting. A minimum occurrence threshold was applied to exclude infrequent terms and reduce noise, and clusters were generated using VOSviewer's default clustering algorithm. Network, overlay, and density visualizations were examined to interpret dominant topics, co-occurrence relationships among keywords, and thematic clusters. Country mapping was based on affiliation metadata to display publication distribution and collaboration linkages. Qualitative analysis was conducted through thematic analysis of article abstracts and full texts to identify major themes related to the role of artificial intelligence in developing metacognitive skills, digital literacy, and artificial intelligence literacy; instructional design and pedagogical strategies; and emerging ethical and pedagogical challenges. Thematic synthesis followed three coding stages. Open coding was used to label segments describing the type of artificial intelligence intervention, pedagogical mechanisms, and reported outcomes. Axial coding was then applied to organize related codes into broader categories. Finally, selective coding was used to consolidate these categories into final themes aligned with the research questions. An evidence matrix was developed to link each study to its artificial intelligence type or mechanism, targeted outcomes, measurement approach, and key findings. This matrix supported cross-study comparison and informed the derivation of implications for physics learning.

FINDINGS

The results section is presented through two complementary layers of analysis. First, bibliometric analysis is used to map publication trends, journal sources, contributing countries, keyword networks, and document characteristics within the selected article corpus. Second, a thematic synthesis of the article's content is conducted to identify patterns in AI-assisted learning interventions, pedagogical approaches, measurement instruments, and implications for the development of metacognitive skills and digital literacy. This separation is intended to ensure clarity regarding the origin of findings and the strength of the evidence presented. In doing so, the bibliometric layer provides a macro-level description of growth and knowledge structure. In contrast, the thematic layer explains how the identified research directions operationalize AI integration and how outcomes related to metacognition and digital literacy are conceptualized and assessed.

RQ1: What are the International Publication Trends Related to Deep Learning–Based AI Integration in Science Learning That Targets Metacognitive Skills and Digital Literacy?

Bibliometric Publication Trends

Scopus data show that the number of publications meeting the search criteria increased sharply between 2020 and 2025. There was 1 article in 2020, 1 in 2021, 2 in 2022, 3 in 2023, 8 in 2024, and 32 in 2025. This growth indicates a clear inflection point beginning in 2024 and culminating in 2025, signaling a transition from an early, low-volume phase into a rapid expansion phase that aligns with the broader adoption of generative AI in education. In proportional terms, 2025 alone accounts for 68.1% of the 47-article corpus, while 2024 to 2025 together account for 85.1%, confirming that research momentum is highly concentrated in the most recent two years. Table 1 summarises the distribution of documents by year and the dominant journals in each year, identified by the highest frequency of occurrence within the article set. Beyond volume growth, the trend is also outlet-specific because the 2024 to 2025 surge is concentrated within a relatively stable set of education and educational technology journals, suggesting the emergence of identifiable publication homes for this topic and practical guidance for future search and dissemination strategies. Consistent with this pattern, early publications appear in Education and Information Technologies and Computers and Education: Artificial Intelligence, while the later expansion is associated with the British Journal of Educational Technology, Education Sciences, Frontiers in Education, Cogent Education, Discover Education, and Computers and Education: Artificial Intelligence.

Table 1. Distribution of documents by year and leading journals

Year	Number of articles	Dominant journals*
2020	1	Education and Information Technologies
2021	1	Computers and Education: Artificial Intelligence
2022	2	Computers and Education: Artificial Intelligence
2023	3	Education Sciences; Cogent Education
2024	8	British Journal of Educational Technology; Computers and Education: Artificial Intelligence; Education Sciences
2025	32	Frontiers in Education; Cogent Education; Discover Education; Computers and Education: Artificial Intelligence

*Dominant journals were identified based on the highest frequency of occurrence within the article set.

Further analysis using the Analyze search results feature in Scopus on the 47 included articles shows that all documents were journal articles (100%). They were dominated by the Social Sciences subject area (49.5%), followed by Computer Science (27.4%), with smaller contributions from Health Professions and Psychology (each 10.5%), and very small proportions from Decision Sciences and Engineering (each 1.1%). This disciplinary configuration indicates that the research is primarily framed as an educational and pedagogical agenda while maintaining a substantive computational foundation that supports AI-enabled learning design, analytics, and adaptive support**.** To address the research question concerning developments over time, the bibliometric analysis first mapped the distribution of publications by year for the 2020–2025 period. This mapping was used to determine whether research on AI–deep learning integration in learning (related to metacognition and digital literacy) was stable, gradually increasing, or experienced a surge in specific years. Accordingly, a Documents by year visualization is presented to illustrate the annual publication trend for the selected dataset (see Figure 2).

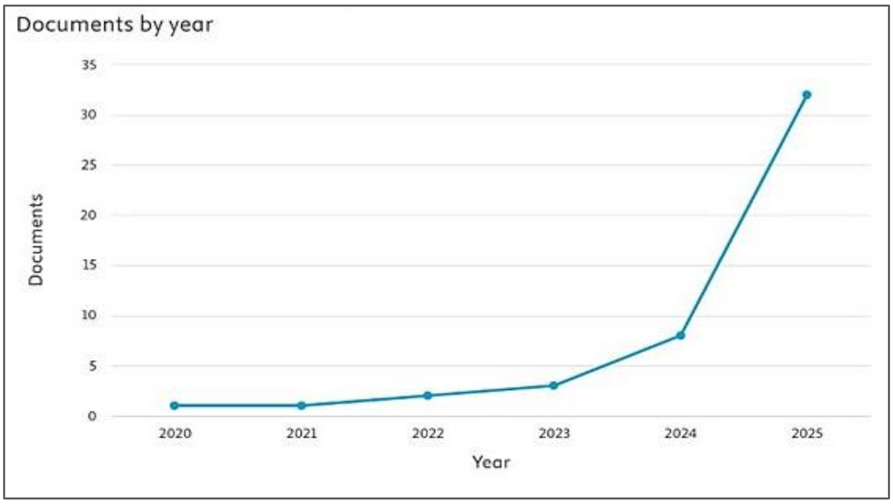


Figure 2. Trend in the number of documents by year

This visualization confirms a very sharp acceleration in publications since 2024, peaking in 2025, indicating that AI–deep learning integration, metacognition, and digital literacy have become mainstream themes in educational research over the last two years. To sharpen the interpretation of this trend, the trajectory can be described as an early low-volume phase from 2020 to 2022, an initial acceleration phase from 2023 to 2024, and a rapid expansion phase from 2025. Beyond examining annual growth, the bibliometric analysis also reviewed the distribution of articles by source/journal to identify the main dissemination channels. A Documents per year by source visualization was used to compare the number of documents per year across several top journals in the dataset, highlighting which journals contributed consistently and during which years publication activity accelerated. In this way, the discussion of trends goes beyond "how many publications" also to address "where they were published" and how journal contribution patterns changed over time (see Figure 3).

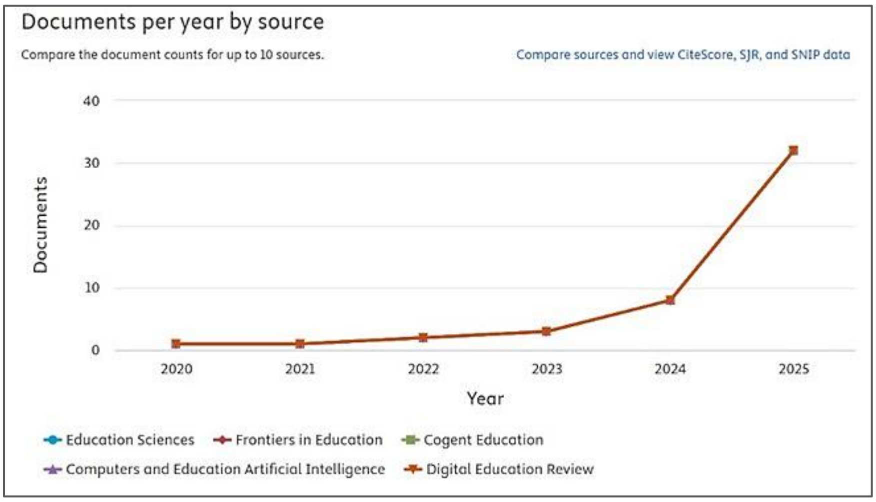


Figure 3. Distribution of documents by year by source/journal

Based on the graph, the surge in publications in the later period, especially 2024–2025, did not occur randomly but was concentrated in several education and educational technology journals that served as the primary publication outlets. This pattern reinforces the aggregate finding that article numbers increased sharply from the early phase of 2020–2022 (still very limited), into an acceleration phase in 2023–2024, and peaked in 2025. The presence of several dominant journals in the graph also suggests that the literature on this topic is beginning to establish relatively clear "publication homes," enabling future literature searches and dissemination strategies to focus on these core journals (Source: Scopus—*Analyze search results*, December 2025). To complement the bibliometric mapping, the analysis also examined the distribution of contributions by country or territory. This mapping is necessary to identify the countries most actively publishing research on AI–deep learning integration in relation to metacognition and digital literacy, while also providing an overview of the geographical spread of research development. Therefore, a Documents by country or territory visualization is presented to compare the number of documents from the top countries in the dataset (see Figure 4).

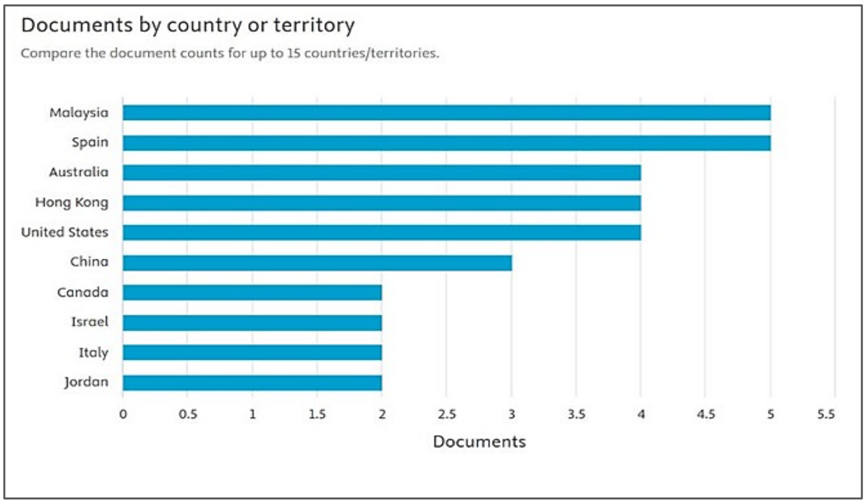


Figure 4. Distribution of documents by country/territory

The graph shows that the highest contributions come from Malaysia and Spain (five documents each). The next contributors are Australia, Hong Kong, and the United States (four documents each), followed by China (three documents), and then Canada, Israel, Italy, and Jordan (two documents each). This distribution suggests an international and multi-regional development pattern rather than concentration within a single national research center. This pattern indicates that research on this topic is developing across regions and is not concentrated in a single country, although several countries appear more prominent within the analyzed dataset. The country network map also shows relatively strong collaborative linkages between Malaysia, Hong Kong, China, and the United States on themes related to AI literacy and digital literacy. At the same time, Jordan and Uganda are shown in relation to the integration of ChatGPT and AI tools for self-directed and e-learning (see Figure 5). Overall, these patterns indicate a multi-regional knowledge base with identifiable collaboration corridors rather than a single dominant national cluster.

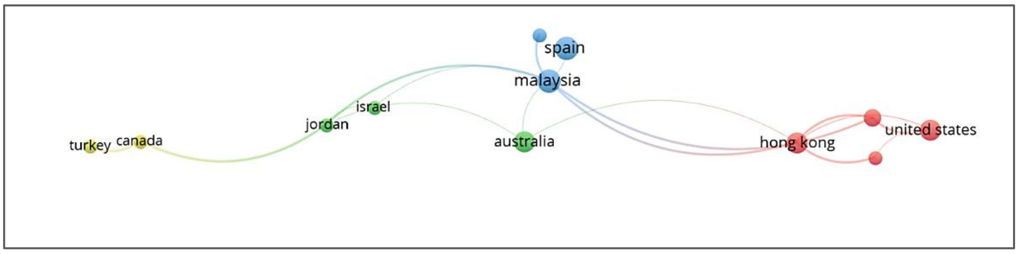


Figure 5. Collaboration network by country

This figure presents a network map of contributing countries, with Malaysia, Spain, Australia, Hong Kong, and the United States as central nodes connected by collaboration links. In contrast, other countries, such as Canada, Turkey, Israel, and Jordan, occupy more peripheral positions. In addition to mapping publication distributions by year, source/journal, and country, the bibliometric profile should also present contributions by author. The purpose of this analysis is to determine whether there are highly dominant authors (an author core) or whether research productivity remains dispersed across many authors with limited contributions. Therefore, a Documents by author visualization is used to compare the number of documents among the top authors in the analyzed dataset (see Figure 6).

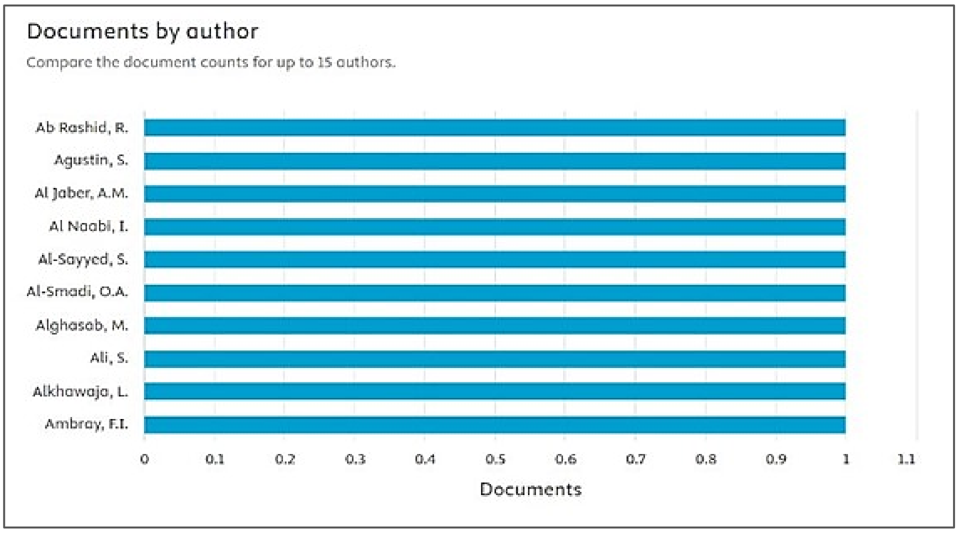


Figure 6. Distribution of documents by author

The graph shows that each of the authors listed at the top has only one document in this dataset, indicating no strong dominance by a single author or a small group. This pattern can be interpreted as evidence that the field is still emerging and relatively dispersed at the author level: many researchers are entering and contributing, but most have not yet formed repeated publication trajectories on the same topic within this dataset. Conceptually, this condition aligns with situations in which a theme is experiencing rapid growth—participation broadens, while a consolidated core of expertise is still forming. Over time, this may become visible through increased collaboration, repeated productivity, and denser co-authorship networks. Beyond mapping trends by year, source/journal, country, and author, the bibliometric analysis also examines contributions by institutional affiliation. Affiliation mapping is important for identifying institutions that appear most frequently in the selected articles, thereby revealing centers of knowledge production and potential institutional networks shaping research on AI–deep learning integration, metacognition, and digital literacy in education. Therefore, a Documents by affiliation visualization is used to compare the number of documents among the top affiliations in the dataset (see Figure 7).

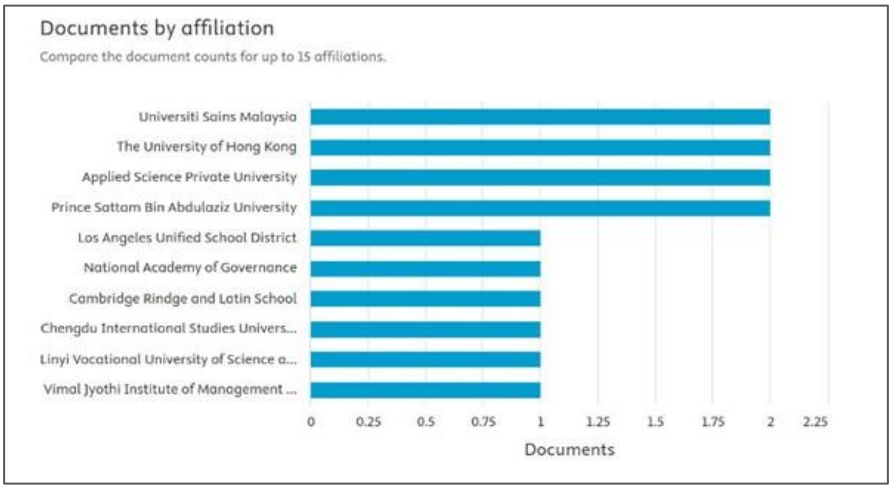
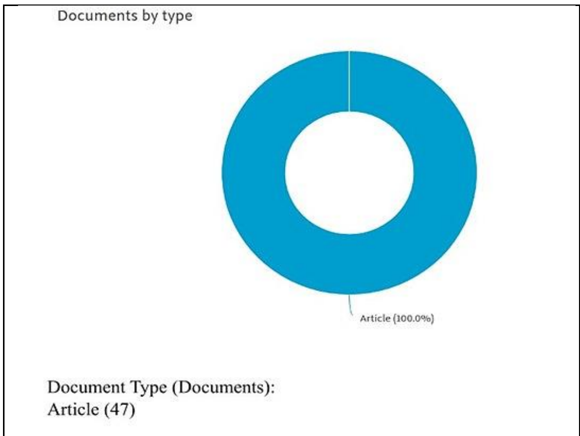
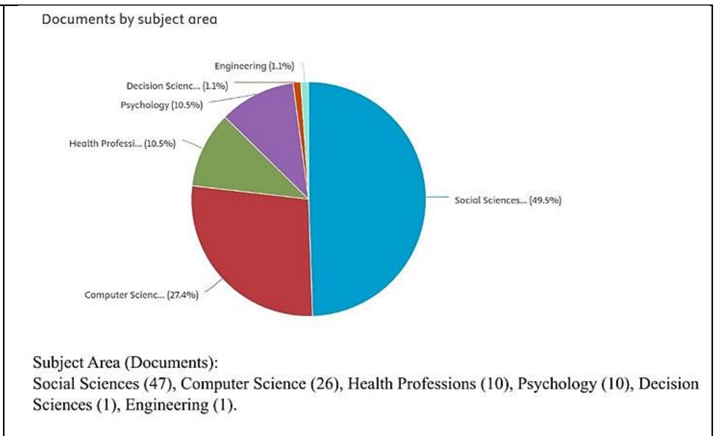


Figure 7. Distribution of documents by institutional affiliation

Based on the graph, several institutions emerge as top contributors with the same or relatively comparable numbers of documents among the leading entries. Prominent affiliations include Universiti Sains Malaysia, The University of Hong Kong, Applied Science Private University, and Prince Sattam Bin Abdulaziz University, each represented by 2 documents in the dataset. In contrast, other affiliations in the subsequent list appear only once. Accordingly, the institutional landscape is better characterized as distributed with a small number of modestly recurrent nodes, rather than dominated by a single center of production. This pattern indicates that institutional contributions remain distributed (not dominated by a single institution). However, a few institutional "nodes" appear more active and may serve as potential references for collaboration, replication of studies, or further literature exploration on this topic. To ensure the consistency and quality of the synthesized evidence, the bibliometric analysis also identifies the composition of document types from the Scopus-selected results. This information is important because different document types (e.g., journal articles, conference proceedings, reviews, or book chapters) may differ in methodological depth and peer-review standards, which can affect how SLR findings are interpreted. Therefore, a Documents by type visualization is presented to show the proportion of document types included in the review (see Figure 8).



(a)



(b)

Figure 8. Distribution by document type (a) and Distribution of documents by subject area (b)

The figure shows that all analyzed documents are journal articles (100%), totaling 47 documents. This finding indicates that the literature synthesis in this study is built entirely on publications that typically undergo peer review, thereby increasing the reliability of the findings compared with a dataset dominated by proceedings or non-journal documents. This profile strengthens the credibility of the mapped trends because the corpus reflects development within formal journal channels rather than being driven by conference proceedings or non-journal outputs**.** Consequently, the trend mapping, publication source analysis, and thematic analysis in this study can be interpreted as a stronger representation of research development within formal academic publication channels (journals) for the 2020–2025 period. In addition to identifying document types, the bibliometric analysis also maps the subject areas of the selected documents to determine which disciplines most prominently address AI–deep learning integration, metacognition, and digital literacy. This information is important because it indicates how the topic is positioned—whether primarily within education/social sciences, computing, or interdisciplinary domains—thereby supporting the interpretation of the methodological context and the evolving research focus. Accordingly, a Documents by subject area visualization is presented to illustrate the disciplinary composition of the analyzed dataset.

The figure shows the dominance of Social Sciences at 49.5%, followed by Computer Science at 27.4%. Other areas contribute smaller proportions, namely Health Professions and Psychology at 10.5% each, and Decision Sciences and Engineering at 1.1% each. This composition confirms that AI–deep learning integration in relation to metacognition and digital literacy is primarily positioned as an education and social science issue, while still maintaining a strong intersection with computing as the technological and analytical foundation. In addition to mapping publication trends, sources/journals, authors, affiliations, document types, and subject areas, the bibliometric analysis also examines funding sponsors recorded in the documents. Funding information helps identify organizations that support research on AI–deep learning integration, metacognition, and digital literacy. It provides an initial picture of the research support ecosystem and possible directions of research priorities. Therefore, a Documents by funding sponsor visualization is presented to compare the number of documents associated with each funding sponsor in this dataset (see Figure 10).

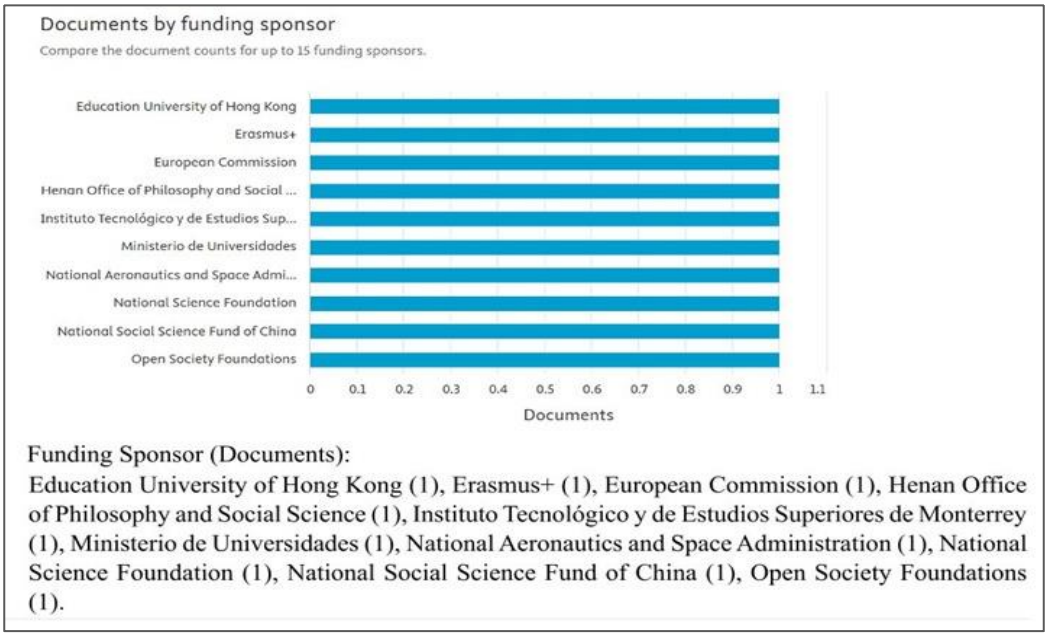


Figure 9. Distribution of documents by funding sponsor

The graph indicates that funding sponsors appearing in the dataset are spread across many organizations, with each sponsor funding only one document in the displayed list. The sponsors include institutions/universities, funding programs, and national and international bodies (e.g., Erasmus and the European Commission), indicating a diversity of research support sources. The one document per sponsor pattern indicates that the funding ecosystem is currently diffuse, suggesting that research priorities are being supported by multiple independent sources rather than coordinated around a single dominant sponsor or program.

Keyword Mapping

Based on the keyword analysis of the 47 articles, the most frequently occurring terms were digital literacy and artificial intelligence, followed by related keywords such as machine learning, educational technology, students, AI literacy, and chatbots. These keywords reflect a strong research focus on digital literacy, AI literacy, and the use of AI technologies in teaching and learning contexts (see Figure 10).

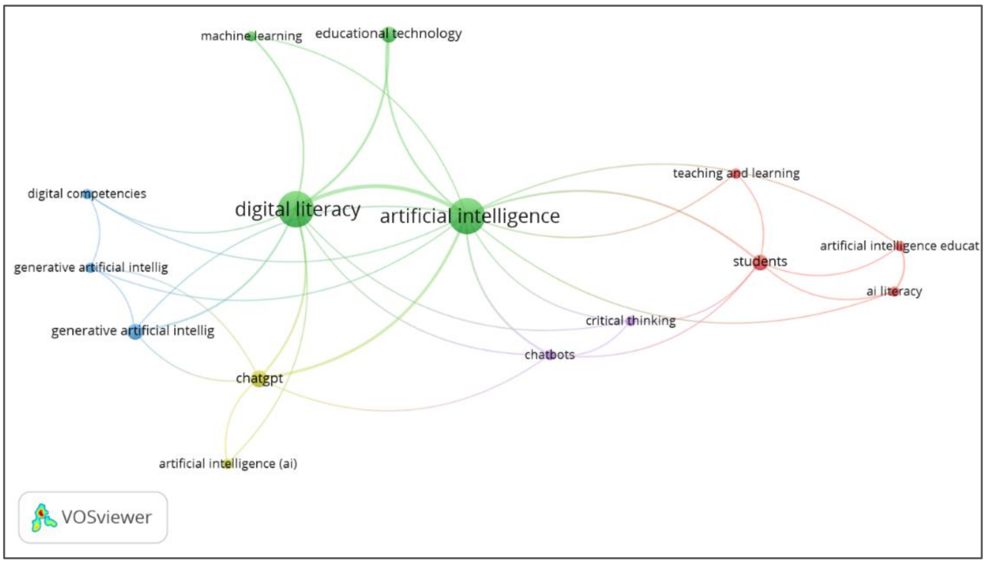


Figure 90. Network of key keyword linkages

This figure shows keyword clusters in which digital literacy and artificial intelligence serve as central nodes, connected to other terms such as educational technology, students, AI literacy, critical thinking, and ChatGPT, indicating thematic relationships among digital literacy, AI use, and learning practices. It should be noted that subject-context mapping at this stage is based on Scopus metadata (title, abstract, and keywords). Therefore, it is possible that some studies are relevant to physics learning but do not explicitly state that context in their metadata. For this reason, the discussion of "implications for physics learning" in this review is positioned as a thematic transfer from cross-context findings (e.g., chatbots/Gen-AI, learning analytics, and adaptive systems) to the specific needs of physics learning, while maintaining a primary focus on strengthening metacognition and digital literacy as the main outcomes.

Availability of Physics Studies in the Corpus (Gap)

Based on Scopus metadata screening of the 47 selected articles (Title, Abstract, Author Keywords, and Index Keywords), no articles were found that explicitly contained the phrase physics education or other markers of a physics learning context (n = 0; 0.0%). In contrast, the corpus largely represents studies on AI integration in general/non-science education (38 articles; 80.9%) and a smaller portion in STEM/science education contexts (9 articles; 19.1%), as indicated by STEM/science markers in the metadata. This finding confirms that physics learning research that explicitly targets metacognitive skills and digital literacy within AI–deep learning integration remains an unfilled space (a research gap) in the mapped publication landscape. Therefore, the contribution to physics learning in this study is not presented as a direct generalization from physics-specific studies, but rather as pedagogical adaptation directions derived from cross-context findings and re-mapped to align with the distinctive characteristics of physics concepts (often abstract), the need for multiple representations, and the demands of problem solving and self-reflection. Overall, these bibliometric findings indicate that research on deep learning–based AI integration in science learning with a focus on metacognition and digital literacy has grown substantially over the past five years. However, it is still dominated by general education and educational technology contexts, with no explicit representation of physics learning. These bibliometric results provide a basis for further examining how AI-assisted learning interventions emerging in science and general education can be translated into adaptation principles for physics learning.

Across the Scopus bibliometric dimensions reported in the dataset (time, sources, geography, authorship, affiliations, funding, and keywords), the most defensible RQ1 inference is a pattern of recent consolidation. The literature shows rapid late-stage growth concentrated in 2024–2025, increasing anchoring in established education and educational-technology outlets, and continued dispersion across authors, institutions, and funders—features that collectively align with an emerging field rather than a mature specialty. Publication output rises sharply after 2023 and peaks in 2025 (32 of 47 documents; 68.09%), while 2024–2025 account for 85.11% of the corpus; in parallel, the endpoint-based CAGR from 2020 to 2025 is 100% per year (from 1 to 32 publications). This growth concentrates within a bounded set of education and educational-technology journals, signaling the emergence of stable publication homes for AI, metacognition, and digital literacy research. Substantively, the topic is education-led yet computationally coupled, consistent with the Social Sciences' prominence alongside a substantial Computer Science interface, as indicated by the dataset and aligned with Scopus's analytical categorization. Country-level contributions are distributed across multiple regions, suggesting international uptake rather than single-country concentration; the reported collaboration links further indicate early-stage network formation, supporting the feasibility of targeted international and comparative research designs. At the same time, the absence of a clear author core and only limited repetition at the affiliation and sponsor levels point to an expanding participation base typical of rapid growth rather than long-standing consolidation around a small set of dominant actors. Finally, physics learning does not appear as an explicit, metadata-labeled context in this corpus, which substantiates a clear gap and justifies a physics-focused adaptation as a contribution framed around transferability and the need for subsequent empirical validation.

RQ2: What Forms of AI-assisted Learning Interventions are Used in Science Contexts, and What is Their Potential for Adaptation to Physics Learning?

RQ2 examines the forms of AI-assisted learning interventions implemented in science and STEM contexts and evaluates their potential for adaptation to physics learning. Consistent with the screening result that the reviewed corpus contains no studies explicitly labeled as physics learning (n = 0; 0.0%), this discussion treats physics as an evidence gap and therefore derives adaptation principles from patterns reported in adjacent science and STEM settings rather than from direct physics trials. Using this approach, the thematic synthesis indicates that AI and deep learning interventions, including generative AI, chatbots, learning analytics, and adaptive systems, can support personalized learning that strengthens metacognitive strategies and digital literacy in science and STEM. For physics, the most plausible adaptation pathways are those that align with physics-specific learning demands, particularly multi-representational reasoning, modeling of abstract phenomena, and quantitative problem solving, which can be supported through simulation-based visualization and data-driven error analysis.

Study Characteristics and Focus

Of the 47 analyzed articles, most employed quantitative approaches using surveys and structural equation modeling (Anthonysamy, 2023; Namatovu & Kyambade, 2025; Xie et al., 2025). Qualitative narrative studies and action research followed these (Al-smadi et al., 2025; Muñoz et al., 2025), as well as several conceptual articles that developed theoretical frameworks for integrating AI and digital literacy (González et al., 2025; Nazari et al., 2024; Tiernan et al., 2023). Most studies were situated in higher education and language-learning contexts, while science and STEM contexts featured in studies on computational thinking, educational robotics, and game-based learning. The main themes can be grouped into the following categories: (a) AI as a mediator of self-regulated learning, metacognition, and mental resilience (Al-smadi et al., 2025; Anthonysamy, 2023). (b) The use of AI tools (ChatGPT, Grammarly, QuillBot, ChatPDF) and their influence on self-directed learning, problem solving, critical thinking, and digital literacy (Alkhawaja et al., 2025; Mwakalinga & Mabilika, 2025). (c) AI literacy and digital literacy in primary and secondary education, including the development of the AILQ instrument and constructivist-based AI literacy programs (Ng et al., 2024; Stasio & Miotti, 2024; Yim & Su, 2025). (d) Computational thinking curricula and educational robotics as pathways toward AI and digital literacy (Falloon, 2024; Stasio & Miotti, 2024; Zammit et al., 2022). (e) Generative AI as a cognitive mediator within critical pedagogical designs aimed at developing computational thinking and critical digital literacy (Muñoz et al., 2025; Tafazoli, 2024). Studies that explicitly addressed physics were scarce. However, findings from computational thinking and science-oriented game-based learning suggest transferable design principles for physics, especially the use of robotics and digital simulations to translate abstract constructs into manipulable models that can be tested through parameter variation and reflective explanation.

The Role of AI and Deep Learning in Learning

Although not all studies explicitly mention deep learning, several describe the use of machine learning and learning analytics within the broader AI and deep learning landscape to personalize learning. The identified forms of integration include: (a) An e-learning satisfaction prediction system using ensemble machine learning methods such as K-Nearest Neighbors and XGBoost to model patterns in students' perceptions (Huang & Khabusi, 2025). (b) Game-based learning that teaches AI and machine learning principles through the ArtBot game, which uses player interaction data to adapt the learning experience (Zammit et al., 2022). (c) The nonformal BANFES system, which uses deep knowledge tracing based on recurrent neural networks to personalize learning pathways in order to address educational access gaps for women in Afghanistan (Nazari et al., 2024). Overall, the findings suggest that deep learning algorithms enable systems to: (a) identify patterns in students' performance and learning difficulties; (b) adjust task difficulty levels and task types; and (c) provide more targeted feedback than rule-based systems. However, direct evidence of their impact on metacognitive skills and digital literacy specifically in physics learning remains limited, which means the current contribution is primarily an adaptation argument rather than a demonstrated physics outcome. The AI-assisted learning interventions identified in this review—such as intelligent tutoring systems, adaptive learning platforms, learning analytics, and generative AI—have primarily been implemented in general science learning contexts. Their strongest conceptual fit for physics lies in three functions: supporting structured problem-solving through step-level feedback, enabling the visualization of abstract concepts through simulation and modeling, and strengthening metacognitive reflection through prompts that elicit assumptions, justify representations, and evaluate solution plausibility. The central finding of RQ2 is therefore that the corpus supports the feasibility of personalized, metacognitively oriented, and digitally literate learning designs using AI in science and STEM. At the same time, physics remains an under-investigated target that warrants direct empirical testing of simulation-supported and analytics-driven implementations.

RQ3: What Instruments Are Used to Measure Metacognitive Skills and Digital Literacy in The Selected Studies, and What is The Potential for Conceptual Adaptation of These Instruments to The Context of Physics Learning?

Measuring Metacognitive Skills

Metacognitive skills in the selected studies were assessed using three thematically aligned approaches that map onto core regulatory processes. First, metacognitive strategy scales adapted from the OSLQ and MSLQ were employed to measure planning, monitoring, and regulation as self-reported strategy use (Anthonysamy, 2023). Second, self-regulated learning indicators were used to represent metacognitive control in online learning, specifically goal setting, time management, structuring the environment, and self-reflection (Al-smadi et al., 2025). Third, qualitative procedures were applied to capture enacted metacognition during generative AI use, including analysis of prompt engineering practices, evaluation of AI outputs, and written reflections as evidence of epistemic vigilance and strategic adjustment (Muñoz et al., 2025). Across these approaches, the dominant pattern indicates that metacognitive regulation is not only an intrapersonal learning resource but also a functional driver of students' capacity to operate effectively in digital learning environments. Consistent with this pattern, metacognitive strategies show a strong positive association with digital literacy, and digital literacy mediates the relationship between metacognition and learning performance in digital contexts (Anthonysamy, 2023). AI integration to support self-regulated learning is reported to facilitate time management and monitoring of understanding. However, the same affordances may increase dependence on external feedback and reduce sensitivity to self-generated error detection when pedagogical scaffolding is insufficient (Al-smadi et al., 2025). Similarly, generative AI use within a critical constructivist framework can strengthen learners' capacity to evaluate prompt quality, assess output consistency, and revise problem-solving strategies, positioning metacognition as an evaluative and corrective mechanism rather than merely a planning routine (Muñoz et al., 2025).

Measuring Digital Literacy and AI Literacy

Digital literacy and AI literacy were measured using a range of instruments, including: (a) Digital literacy scales based on technical, cognitive, and socio-emotional dimensions drawing on Ng et al. (2024) and Laer & Elen (2017), often combined with indicators of learning performance and mental resilience (Anthonysamy, 2023). (b) The AI Literacy Questionnaire (AILQ), which measures four ABCE dimensions: Affective (motivation, self-efficacy), Behavioral (commitment and collaboration), Cognitive (AI knowledge and skills), and Ethical (privacy, security, and social responsibility) (Ng et al., 2024). (c) Perception-based instruments assessing how AI tools influence self-directed learning, problem solving, critical thinking, and digital literacy, developed in studies on AI for educational quality literacy (Alkhawaja et al., 2025) and on ChatGPT adoption (Namatovu & Kyambade, 2025). (d) Student grouping by digital literacy level (e.g., weaker vs. stronger) to examine differences in acceptance of AI e-books (Xie et al., 2025). Overall, the findings suggest that: (a) Digital literacy functions as an important mediator between metacognitive strategies and learning performance; improving digital literacy strengthens students' ability to leverage AI-based resources for independent learning (Anthonysamy, 2023). (b) AI tools such as Grammarly, ChatGPT, QuillBot, and ChatPDF are perceived as capable of improving digital literacy through practices such as text manipulation, summarization, information evaluation, and interaction with complex documents. However, these claims are still largely based on self-reports (Alkhawaja et al., 2025). (c) AI literacy programs in primary and secondary education designed around constructivism and project-based learning produce significant improvements in the cognitive and ethical dimensions, while also strengthening positive attitudes toward AI (Ng et al., 2024; Yim & Su, 2025).

Measurement Instruments and Conceptual Adaptation for Physics Learning

Although the OSLQ, MSLQ, and AILQ are widely used and psychometrically established in general contexts, the measurement logic in the selected studies remains dominated by self-report, which constrains interpretability when transferred to physics learning. Physics learning requires sustained quantitative problem solving, coordination of multiple representations such as graphs, diagrams, and equations, and explicit evaluation of the validity of reasoning chains and numerical results. Accordingly, conceptual adaptation should preserve the theoretical constructs captured by existing scales while shifting the assessment focus toward observable regulation during authentic physics tasks. This adaptation can be operationalized through task-based instruments that assess strategic planning for selecting and sequencing solution procedures, monitoring representational consistency across mathematical, graphical, and conceptual forms, and evaluating numerical plausibility through estimation, unit analysis, and boundary checking. In parallel, digital and AI literacy in physics should be measured through performance tasks that require students to verify AI-generated explanations against physical principles, justify acceptance or rejection of outputs with evidence, and document iterative revisions to their reasoning and representations. These directions sharpen the alignment between measurement and domain epistemology, indicating that valid assessment of metacognition and digital literacy in physics must be sensitive to scientific reasoning, representational competence, and quantitative validation, rather than relying primarily on general self-report indicators.

RQ4: What Pedagogical Implications Can be Formulated from the Literature for Developing AI–Deep Learning–Based Science Learning Designs Oriented Toward Strengthening Metacognition and Digital Literacy, and What is The Direction of Their Conceptual Adaptation for Physics Learning?

Based on the literature review, the pedagogical implications of integrating deep learning–based AI into science learning include shifting instructional design toward adaptive, reflective, and data-driven approaches. This shift is evidenced by the concentration of reviewed interventions in digital learning environments that generate learner traces and use them to deliver adaptive guidance, with the primary instructional purpose moving from answer delivery to supporting self-regulated learning processes. In physics learning, these implications can be conceptually adapted by using AI to support higher-order thinking processes, such as planning problem-solving strategies, monitoring conceptual understanding, and reflecting on solution approaches. Thus, AI is not positioned as a replacement for the teacher, but as a cognitive tool that strengthens learners' metacognition and digital literacy. Importantly, the review also indicates that the empirical basis for these implications is largely drawn from general science education, STEM, and educational technology contexts, and that physics learning remains a strategic gap, so the physics-oriented statements below should be read as a conceptual adaptation agenda rather than an empirically validated physics model.

AI–deep Learning and Metacognition

The literature synthesis indicates that integrating AI–deep learning into science learning can strengthen metacognition through adaptive feedback, personalized recommendations, and digital learning environments that facilitate planning, monitoring, and evaluation of learning (Anthonysamy, 2023). Common forms of integration include intelligent tutoring systems, learning analytics, conversational agents (chatbots), AI e-books, and the use of generative AI to provide more responsive, interaction-rich learning support (Xie et al., 2025; Zammit et al., 2022). Consequently, AI–deep learning–based science learning designs should shift AI's role from an "answer machine" to a reflection partner that triggers metacognitive strategies through higher-order questioning, feedback based on error analysis, and tasks that require justification of reasoning processes (Anthonysamy, 2023; Muñoz et al., 2025). This implies a design principle in which AI interactions are intentionally structured to elicit metacognitive regulation, meaning that prompts and feedback should target decisions and reasoning moves, such as identifying assumptions, selecting representations, and explaining why a strategy is appropriate, rather than merely confirming correctness.

In the context of self-regulated learning, tools such as chatbots and automated feedback systems can help learners set goals, manage study time, and monitor understanding, but they must be accompanied by guidance to avoid fostering dependence (Al-smadi et al., 2025; Ibeh et al., 2025). Practical implementation directions that can be stated as pedagogical implications for science learning include: (a) Integrate metacognitive prompts (e.g., check assumptions, check representations, check calculation steps/arguments) as part of learners' dialogue with AI. (b) Use AI to provide process-oriented feedback (strategy/argumentation), not merely to verify final answers. (c) Use learning analytics to detect error patterns and provide scaffolding that encourages self-monitoring.

Digital literacy and AI literacy

The review confirms that digital literacy is a prerequisite for metacognitive strategies to be effective in digital environments, because it functions as a mediator linking metacognition to learning performance (Anthonysamy, 2023). In the context of rapid AI development, AI literacy is positioned as part of digital literacy. It includes affective, behavioral, cognitive, and ethical dimensions (ABCE), enabling learners to understand how AI works, its limitations, and the social consequences of AI use (Ng et al., 2024; Reyes et al., 2025; Tiernan et al., 2023). Studies on AI literacy at the school level also highlight the importance of constructivist and project-based designs to promote meaningful interaction with intelligent agents, computational thinking, critical data literacy, and AI ethics (Yim & Su, 2025). The pedagogical implication is that digital and AI literacy should be stated as explicit learning outcomes in science modules, operationalized through verification tasks that require students to evaluate the credibility of AI outputs, test conceptual consistency against scientific principles or data, and provide clear rationales and sources when accepting or rejecting AI-generated claims (Muñoz et al., 2025). In addition, assessment should move beyond self-report by using ABCE-aligned rubrics that capture observable practices, including verification behaviors, calibrated trust and attitudes, conceptual understanding of AI limitations, and ethical decision-making in AI-supported work (Ng et al., 2024).

Ethical Challenges in Learning

The synthesized literature also highlights ethical and pedagogical challenges, including plagiarism, information reliability, bias, data privacy, and the risk of reduced deep cognitive engagement when generative AI is used without guidance (Ibeh et al., 2025; Jwair, 2025; Tiernan et al., 2023). In addition, several studies report positive but ambivalent attitudes toward generative AI: it is seen as improving efficiency and task quality, yet it is also feared to erode critical thinking and the quality of pedagogical interaction if not regulated (Haroud & Saqri, 2025; Lozano & Fontao, 2023; Mwakalinga & Mabilika, 2025). Pedagogical implications that can be stated in this section include: (a) Establish classroom rules for AI use (what is allowed/not allowed), mandatory disclosure of AI use, and citation/acknowledgment standards. (b) Shift assessment toward evidence of process (step-by-step work, reflective journals, dialogue logs, and argumentation) so that AI does not become a shortcut to final products. (c) Emphasize the teacher’s role as an AI-informed pedagogue who guides responsible AI use and safeguards learners’ epistemic agency (Lozano & Fontao, 2023; Tiernan et al., 2023). This governance also clarifies the teacher's role as an AI-informed pedagogue who orchestrates tasks, sets boundaries, and supports critical evaluation, so that AI use strengthens rather than replaces disciplined reasoning.

Direction of Adaptation for Physics Learning: Implementing AI–Deep Learning to Strengthen Metacognition and Digital/AI Literacy

The direction of adaptation for physics learning is derived from the synthesis of science learning, with a focus on the needs of multiple representations (phenomena, diagrams, graphs, equations) and problem solving, so that AI does not function as an "answer machine" but as a mediator that prompts learners' metacognitive reflection. Within this framework, AI–deep learning is used to support learners in planning (planning), monitoring conceptual understanding and solution steps (monitoring), and evaluating the plausibility of results and representational consistency (evaluating) throughout physics learning. Conceptually, this adaptation can be formalized as a design cycle in which the learning environment captures physics specific learning traces, such as responses to conceptual questions, intermediate problem solving steps, and interaction logs with representations, then models knowledge states and error patterns using AI and deep learning methods, and finally delivers adaptive scaffolding that is explicitly metacognitive, for example prompts to check assumptions in a free body diagram, verify unit consistency, reconcile graph shape with equations, or justify the chosen representation. Implementation can be strengthened through digital learning environments such as intelligent tutoring systems, chatbots/generative AI, learning analytics, AI e-books, and simulations that enable independent exploration supported by data-driven feedback. To maintain learning quality, physics adaptation should be accompanied by strengthened digital and AI literacy and an emphasis on the ethics of AI use, so that risks related to dependence, academic integrity, and the quality of critical evaluation of AI outputs remain manageable. Accordingly, the principal contribution of this review to RQ4 is the formulation of a coherent pedagogical direction for physics, namely positioning AI as a cognitive and metacognitive tool that supports multi-representational problem-solving while simultaneously developing verification-oriented digital and AI literacy, even though direct empirical evidence in physics contexts has not yet been identified.

Study Limitations

This review has several limitations. First, most of the analyzed studies used self-report instruments to measure metacognitive skills and digital literacy, which may not fully reflect learners' actual performance in physics problem-solving. Second, no articles were found that explicitly examined deep learning–based AI integration in physics learning; therefore, the findings of this review are conceptual and adaptive, rather than empirically generalizable. Third, the educational contexts represented in the analyzed articles are dominated by general education and educational technology, which requires further adjustment when applied to physics learning. Based on the mapping in Table 2, physics learning remains a strategic research gap. Future studies should design and test AI-assisted physics interventions that explicitly target planning, monitoring, and evaluating during multi-representational problem solving, and that assess these outcomes using task-based measures and ABCE-aligned literacy indicators rather than relying primarily on self-report.

Table 2. Linkages Between the Research Questions, Key Findings, and Implications for Physics Learning

No.	Research Question (RQ)	Key Findings of the Review	Conceptual Implications for Physics Learning
1	RQ1: Publication trends on AI–deep learning integration, metacognition, and digital literacy	Publications have increased significantly since 2023 and are dominated by general education and educational technology contexts; no physics learning studies were found explicitly.	Physics learning emerges as a strategic research gap for developing deep learning–based AI integration research.
2	RQ2: Forms of AI-assisted learning interventions and their adaptation potential	The main interventions include intelligent tutoring systems, adaptive learning, learning analytics, and generative AI.	These interventions can be conceptually adapted to support problem solving, concept visualization, and metacognitive reflection in physics.
3	RQ3: Instruments for measuring metacognition and digital literacy	Measurement is dominated by self-report instruments (MSLQ, OSLQ, AI literacy scales), with limitations in task-specific contexts.	Task-based instruments tailored to physics are needed to assess planning, monitoring, and evaluation during problem solving.
4	RQ4: Pedagogical implications and adaptation directions	AI functions as a tool to support adaptive and reflective learning.	AI-based physics learning design should emphasize AI as a cognitive tool for strengthening metacognition and digital literacy.

Based on Table 2, the integration of deep learning–based artificial intelligence in physics learning remains conceptual and adaptive, with findings largely derived from science education and broader STEM contexts. This mapping highlights physics learning as a strategic research gap, particularly for developing AI-assisted interventions that explicitly target metacognitive skills and digital literacy through pedagogical designs that position AI as a cognitive tool in physics problem solving.

DISCUSSION

The bibliometric findings indicate that international publications on AI integration—spanning deep learning, learning analytics, adaptive systems, and generative AI—targeting metacognition and digital literacy accelerated markedly during 2024–2025. Rather than reflecting simple linear growth, this surge signals a transition in the field. Research on AI in education is shifting from exploratory adoption studies toward learning design and competency-oriented agendas, influenced by the widespread diffusion of generative AI in classrooms. Publication outlets also appear increasingly concentrated in education and educational technology journals, while geographic contributions are distributed across multiple countries. Analytically, this concentration suggests that the dominant framing of AI and learning is primarily shaped by pedagogical and educational technology discourses, such as design, feedback, literacy, and ethics, rather than solely by computer science venues. This situation underscores the importance of theory-informed learning mechanisms and rigorous assessment. However, within the metadata of the selected corpus, no studies were found that were explicitly labeled *as physics education* (n = 0). This gap is better understood as an intersectional void, namely the intersection of AI, metacognition, digital or AI literacy, and physics context, rather than as evidence that AI is absent from physics education in general. Physics-related AI studies may exist, but they may not foreground metacognition or digital literacy in titles or keywords, or they may be indexed under related terms.

Nevertheless, the absence of explicitly labeled physics studies remains scientifically consequential because it prevents the accumulation of comparable evidence on how AI interventions foster metacognitive regulation and literacy competencies in response to the distinctive epistemic demands of physics. This situation positions physics learning as a strategic research gap for further development. The thematic synthesis across science/STEM and general education contexts shows that the dominant intervention types include intelligent tutoring systems, adaptive learning, learning analytics, AI e-books, and chatbots/generative AI that function as cognitive mediators for learning personalization and reflective support (Anthonysamy, 2023; Xie et al., 2025; Zammit et al., 2022). Given the absence of physics-specific empirical evidence, the adaptation potential for physics is derived primarily at a conceptual level: AI should be directed to facilitate visualization of abstract concepts, diagnose error patterns, and provide data-driven problem-solving scaffolding—rather than acting as an answer machine, so that it aligns with the characteristics of physics learning, which demands problem solving and consistency across multiple representations (Maries & Singh, 2023; Munfaridah et al., 2021).

From a measurement perspective, instruments for metacognition and digital/AI literacy in the selected studies are dominated by self-report approaches, such as metacognitive strategy scales and self-regulated learning measures rooted in traditions of metacognition and learning regulation (Tadesse et al., 2022; Wang et al., 2025). These measures often adopt or adapt the MSLQ/OSLQ and broader SRL indicators (Al-smadi et al., 2025; Anthonysamy, 2023). Digital literacy is commonly operationalized through technical–cognitive–socio-emotional dimensions (Ng et al., 2024). In contrast, AI literacy is developing through instruments and competency frameworks that emphasize understanding AI concepts, usage practices, and ethical dimensions (e.g., AILQ/ABCE and broader conceptualizations of AI literacy as a set of competencies) (Long & Magerko, 2020; Ng et al., 2024). Methodologically, heavy reliance on self-report limits causal interpretation because perceived strategy use may not match actual strategy enactment, especially in domains that require multi-step quantitative reasoning. In physics, this limitation is even more salient. Metacognition should be evidenced through learners' actions while solving problems, such as planning moves, checking representations, and testing plausibility, not only through what learners believe they do. Accordingly, a physics-sensitive measurement agenda should triangulate task-based performance indicators, process traces such as interaction logs and solution step sequences, and reflective artifacts such as journals or explanation rubrics, so that regulation and literacy are captured as enacted competencies.

Based on these findings, a key pedagogical implication is that AI–deep learning–based science learning design should position AI as a cognitive–metacognitive tool that activates the planning–monitoring–evaluating cycle through metacognitive prompts, process-oriented feedback, and error analytics to strengthen thinking strategies. At the same time, digital/AI literacy goals and ethical governance must be stated explicitly—including disclosure of AI use, privacy, bias, and academic integrity—so that risks such as dependence and reduced deep cognitive engagement can be minimized (Muñoz et al., 2025; Tiernan et al., 2023). In this context, the ABCE framing is analytically useful because it clarifies that effective AI use requires not only cognitive knowledge of AI, but also behavioral routines such as verification practices, affective readiness such as calibrated self-efficacy without over-trust, and ethical judgment related to privacy and integrity. In physics contexts, the limitations of self-report approaches further reinforce the urgency of adapting measurement toward task-based assessment that is sensitive to quantitative problem solving and representational consistency (diagrams–graphs–equations), so that evidence of metacognition and digital/AI literacy is reflected through performance and process traces rather than perceptions alone (Picardal, 2025; Zeivots et al., 2025).

Overall, these implications suggest that the development of AI-based science learning, especially in physics, should focus on two main agendas. First, AI should be designed as a cognitive and metacognitive tool that supports planning, monitoring, and evaluation through metacognitive prompts, process-oriented feedback rather than final-answer verification, and scaffolding based on error analytics, in order to strengthen problem-solving and multi-representational consistency across diagrams, graphs, and equations. Second, digital and AI literacy, along with ethical governance, including AI use disclosure, privacy, bias, and academic integrity, must be strengthened as prerequisites so that AI use does not reduce cognitive engagement or create dependence, but instead improves learners' capacity to evaluate the credibility and limitations of AI outputs. Scientifically, this review contributes by evidencing the growth and disciplinary concentration of the field through bibliometric mapping, integrating intervention mechanisms with metacognition and literacy constructs to explain how AI can support regulation rather than only whether it is adopted, and translating cross-context evidence into a physics-oriented design and measurement agenda that is ready for empirical testing. Because the corpus does not yet provide physics education-specific empirical evidence, the next step is to conduct design-based and experimental studies in physics that compare AI used primarily for answer production with AI designed as scaffolding, using task-based and trace-based measures to test effects on representational consistency, error diagnosis, and metacognitive regulation over time.

CONCLUSION

This systematic literature review and bibliometric analysis confirm that research on deep learning–based artificial intelligence in education has accelerated significantly since 2023, particularly in relation to digital literacy, AI literacy, and self-regulated learning; however, the absence of studies explicitly situated in physics learning (n = 0) demonstrates a clear and empirically evidenced research gap. By combining SLR and bibliometric mapping, this study contributes theoretically through a structured knowledge map linking AI, metacognition, and digital/AI literacy, and conceptually through an adaptation framework that repositions AI as a cognitive–metacognitive mediator in physics problem solving rather than as a mere answer-generating tool. The findings imply that future AI-supported physics learning designs should explicitly integrate metacognitive cycles (planning–monitoring–evaluating), adopt more robust and task-based assessments beyond self-report instruments, and embed digital/AI literacy and ethical governance (e.g., academic integrity, bias awareness, and responsible use) as core instructional components. At the same time, the study is limited by its reliance on Scopus-indexed articles, specific keyword constraints, and the dominance of non-physics and higher-education contexts, meaning that the proposed framework remains conceptual and requires empirical validation. Therefore, the next critical step for advancing the field is the design and experimental testing of AI-assisted interventions in secondary and tertiary physics classrooms, using longitudinal and mixed-method approaches to generate stronger evidence on how AI can authentically enhance metacognition and digital literacy within the distinctive epistemic structure of physics learning.

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