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From Ethnoscience to Digital Inquiry: Mapping Research Trends and Gaps in Critical Thinking and Digital Literacy within STEM Education

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Abstract: The integration of ethnoscience, digital technology, and inquiry-based learning in STEM education has become an increasingly important focus in science education research. This systematic literature review aims to map research trends, identify effective models, and reveal gaps related to critical thinking skills and digital literacy in STEM-based science learning. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method, 101 articles published from 2010 to 2026 were selected from Scopus (Q1–Q3) and SINTA (S1–S2) indexed journals. Data from Dimensions AI (4,095 total publications, 2017–2026) and VOSviewer bibliometric mapping (232 items, 5 clusters) further contextualize the research landscape. The analysis reveals five dominant themes: (1) Ethno-STEM and project-based learning, (2) augmented and virtual reality in science learning, (3) development of critical thinking skills through inquiry-based approaches, (4) digital literacy in education, and (5) innovative STEM learning models. The findings indicate that inquiry-based approaches, when combined with local cultural integration (ethnoscience) and digital technology, are effective in improving students' critical thinking skills. However, research on the integrated development of a specific model that simultaneously addresses ethnoscience, digital inquiry, and STEM remains limited. This study provides a theoretical foundation for developing an innovative learning model that bridges local cultural wisdom with 21st-century digital competencies.

Keywords: critical thinking, digital literacy, ethnoscience, inquiry-based learning, STEM education.

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INTRODUCTION

Science education in the 21st century faces significant challenges in preparing learners who not only master scientific content but are also capable of critical thinking, digitally literate, and sensitive to local wisdom. Global data from Dimensions AI records more than 4,095 scientific publications (2017–2026) examining the topics of ethnoscience, digital technology, and inquiry in STEM education, demonstrating the enormous scale of global academic attention directed toward this issue. The STEM (Science, Technology, Engineering, and Mathematics) approach has been demonstrated to constitute an effective learning framework for integrating various disciplines in addressing contemporary educational challenges (Han et al., 2016; Bara & Xhomara, 2020). However, the global implementation of STEM often overlooks the rich local cultural contexts that are highly relevant to Indonesian students.

Ethnoscience is an approach that integrates scientific knowledge with local wisdom and has received significant attention as a solution for bridging Western science with students' cultural experiences (Sumarni & Kadarwati, 2020;

Atmojo et al., 2025). Research indicates that integrating ethnoscience into learning not only enhances students' learning motivation but also strengthens conceptual understanding and higher-order thinking skills (Rosyidah et al., 2025; Winarto et al., 2022). Furthermore, the urgency of ethnoscience for Indonesia is reflected in the study by Tohri et al. (2022) concerning Sasak local wisdom in Lombok, which demonstrates that local wisdom is relevant as a foundation for character education. The results further confirm that introducing ethnoscience in junior secondary schools clearly improves students' scientific literacy (Jufrida et al., 2024).

Despite its recognized educational value, integrating ethnoscience into digital learning environments remains conceptually and pedagogically challenging. Ethnoscientific knowledge is inherently contextual, experiential, and socially transmitted through cultural practices. In contrast, immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) are generally designed to represent standardized scientific concepts and technologically mediated interactions. This epistemological mismatch often results in local cultural knowledge being reduced to superficial visual representations rather than functioning as an authentic source of scientific inquiry. Furthermore, previous studies emphasize that teachers frequently experience difficulties in transforming indigenous knowledge into inquiry-oriented digital learning activities because of limited pedagogical frameworks, insufficient digital competencies, and the absence of culturally responsive instructional design guidelines (Hinostroza et al., 2024; Atmojo et al., 2025; Verawati et al., 2025). Consequently, although immersive technologies provide promising opportunities for contextual science learning, their integration with ethnoscience remains fragmented and lacks a coherent theoretical foundation that simultaneously accommodates the development of digital literacy, inquiry processes, and cultural authenticity.

The development of digital technology, particularly Augmented Reality (AR) and Virtual Reality (VR), creates new opportunities for immersive and interactive learning experiences. Numerous studies have demonstrated the effectiveness of AR/VR technology in enhancing students' motivation, conceptual understanding, and critical thinking skills in science learning (Prananta et al., 2024; Prahani et al., 2022; Widiyatmoko et al., 2023; Citra & Anggaryani, 2022). Researchers earlier developed an Android-based AR medium for the human excretory system material that received positive responses from students (Qumillaila et al., 2017). Moreover, digital inquiry-based approaches have been proven capable of promoting active engagement and the development of students' digital literacy (Perdana et al., 2020; Hinostroza et al., 2024). The integration of ethnoscience with AR and inquiry has even been demonstrated to enhance creativity and learning motivation among physics students (Ainur et al., 2025).

Critical thinking skills represent an essential 21st-century competency that must be developed systematically. The research findings reveal a gap between students' perceptions of their critical thinking abilities and their actual performance; students tend to perceive themselves as more critical than they actually are (Afikah et al., 2024). The comparative study demonstrates that NHT, PBL, and integrated NHT-PBL learning approaches produce significant differences in critical thinking skills based on students' prior ability levels (Rijal et al., 2021). At the tertiary level, researchers report that the critical thinking profile of university students still requires improvement, particularly in the indicators of evaluation and inference (Suciati et al., 2022), while another researcher conducted a longitudinal investigation into teachers' understanding of critical thinking (Özelçi & Çalýþkan, 2019). Through a mixed-methods analysis, confirm that critical thinking training significantly improves critical thinking ability and academic achievement (Batdý et al., 2024).

Critical thinking in this review is interpreted using Facione's Delphi framework, which conceptualizes critical thinking as purposeful and self-regulated judgment involving six core cognitive skills: interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 1990). This framework was adopted because it has become one of the most widely accepted theoretical references in science and STEM education and provides a consistent basis for interpreting the effectiveness of instructional interventions across diverse empirical studies. Although the reviewed articles employed different assessment instruments, their reported outcomes were synthesized according to these six dimensions whenever comparable evidence was available.

Although numerous studies have separately examined aspects of ethnoscience, digital technology, inquiry, and STEM learning, no systematic review has yet comprehensively mapped the integration of these three elements, particularly within the context of developing a holistic learning model. A bibliometric analysis using VOSviewer of 232 keyword items in 5 clusters from the relevant literature confirms that the ethnoscience-STEM-digital inquiry integration cluster remains minimally represented compared to conventional instructional methodology clusters. Based on this gap, the present study addresses the following Research Questions (RQ):

1. RQ1: What are the research trends in ethnoscience, digital technology, inquiry, digital literacy, and critical thinking in STEM education?
2. RQ2: Which learning models are effective in developing critical thinking and digital literacy?
3. RQ3: What research gaps underlie the development of an innovative learning model?
4. RQ4: What recommendations support future research and innovative learning model development?

METHOD

Research Design

This study employs a Systematic Literature Review (SLR) method using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach. The PRISMA method was selected because it provides a transparent, systematic, and reproducible protocol for the selection and synthesis of scientific literature (Verawati et al., 2025). Several previous studies have employed similar PRISMA approaches to map research trends in the fields of STEM and digital literacy, such as Prananta et al. (2024) in a bibliometric analysis of AR in science, and in the mapping of global digital literacy research (Sogalrey et al., 2024).

Search Strategy

The literature search was conducted using two complementary strategies. First, an international-level search was carried out directly in the Scopus database (restricted to Quartile 1–3 journals) using the structured Boolean string described below. Second, because SINTA functions as an indexing portal rather than a Boolean-searchable database, nationally indexed literature was retrieved through Google Scholar, used strictly as a search engine, after which each retrieved article was individually verified against the SINTA portal (sinta.kemdikbud.go.id) to confirm that its source journal was accredited SINTA 1–2; only articles passing this verification step were retained. In Google Scholar, the "journal ranking" indexing display feature was enabled, allowing search results to be manually filtered within Google Scholar itself, after which each candidate journal was re-verified against the SINTA platform. Rather than relying on loosely combined general keywords, the search was conducted using structured Boolean search strings with explicit field-specific parameters (e.g., TITLE-ABS-KEY for Scopus) to ensure a systematic, transparent, and replicable search process; the complete search strings applied to Scopus and Dimensions AI are presented in Table 1. The search was restricted to articles published between 2010 and 2026. In addition to journal databases, supplementary bibliometric analysis was conducted through the Dimensions AI platform (app.dimensions.ai) using the structured query detailed in Table 1, which yielded publication trend data from 2017 to 2026.

Table 1. Search strings and search/verification procedures used for scopus, dimensions AI, and google scholar (SINTA 1–2) searches

Database	Boolean Search String (Query)	Search Field / Parameters & Filters
Scopus	TITLE-ABS-KEY (("ethnoscience" OR "ethno-STEM" OR "local wisdom" OR "indigenous knowledge") AND ("digital technology" OR "augmented reality" OR "virtual reality" OR "ICT") AND ("inquiry" OR "inquiry-based learning" OR "digital inquiry") AND ("critical thinking" OR "digital literacy") AND ("STEM" OR "STEM education" OR "science education"))	Field: TITLE-ABS-KEY. Filters: PUBYEAR > 2009 AND PUBYEAR < 2027; DOCTYPE("ar"); LANGUAGE("English" OR "Indonesian"); SUBJAREA("SOCI" OR "MULT").
Dimensions AI	("ethnoscience" OR "local wisdom" OR "indigenous knowledge") AND ("digital technology" OR "augmented reality" OR "virtual reality" OR ICT) AND ("inquiry" OR "inquiry-based learning") AND ("STEM education" OR "science education")	Search field: Title and Abstract (Advanced Search). Filters: Publication Year 2017–2026; Source type: Article; Category: Education.
Google Scholar (SINTA 1–2 verification)	Step 1 – Advanced Scholar Search form (scholar.google.com/advanced_scholar_search): "with all of the words" = ethnoscience local wisdom indigenous knowledge; "with at least one of the words" = "digital technology" "augmented reality" "virtual reality" ICT inquiry "inquiry-based learning" "STEM education" "science education" "critical thinking" "digital literacy"; "where my words occur" = in the title of the article. Step 2 – each retrieved record was opened, and its publishing journal name was checked one by one against the official accredited-journal list on the SINTA portal (sinta.kemdikbud.go.id/journals), filtered to Accreditation = S1 and S2. Step 3 – only records whose source journal appeared on this S1/S2 list were retained; records from unaccredited or Scopus-indexed journals already captured in the Scopus search were discarded to avoid duplication.	Search field: Article title (title-restricted search). Filters: manually applied – Publication Year 2010–2026; Document type: journal article; Accreditation: SINTA 1–2 only (verified via sinta.kemdikbud.go.id/journals).

Note: Boolean operators (AND, OR) and field-restricted parameters were applied to ensure that the search results were reproducible and consistently aligned with the scope of ethnoscience, digital technology, inquiry, digital literacy, and critical thinking within STEM education.

Inclusion and Exclusion Criteria

The inclusion criteria comprised: (1) empirical research articles or literature reviews published in reputable journals (Scopus Q1–Q3 or SINTA S1–S2); (2) topics related to ethnoscience, digital technology (AR/VR), inquiry, digital literacy, critical thinking, and/or STEM learning; (3) an educational context at the primary, secondary, or tertiary level; and (4) articles published in Indonesian or English. The exclusion criteria comprised: (1) articles for which the full text was unavailable; (2) conference proceedings; (3) articles outside the publication range of 2010–2026; and (4) articles deemed irrelevant following full-text reading.

PRISMA Selection Process

The article selection process followed the PRISMA 2020 flow diagram, comprising four stages: (1) Identification: database searching across Scopus (Q1–Q3) and Google Scholar (SINTA S1–S2) using the Boolean search strings presented in Table 1 yielded 387 records; after removing 27 duplicate records and 14 records marked as ineligible by automation tools, 346 records remained for screening; (2) Screening: title and abstract screening excluded 157 irrelevant records, leaving 189 reports sought for retrieval, of which 11 could not be retrieved; (3) Eligibility: the remaining 178 reports were assessed for eligibility through full-text reading combined with the structured quality appraisal described in the following subsection, resulting in the exclusion of 77 reports (conference proceedings, n = 24; full-text unavailable, n = 18; outside the 2010–2026 publication window, n = 16; and irrelevant to the research objectives or failing to meet the minimum methodological quality threshold, n = 19); and (4) Included: the final 101 studies were retained for in-depth analysis. The complete PRISMA flow diagram is presented in Figure 1.

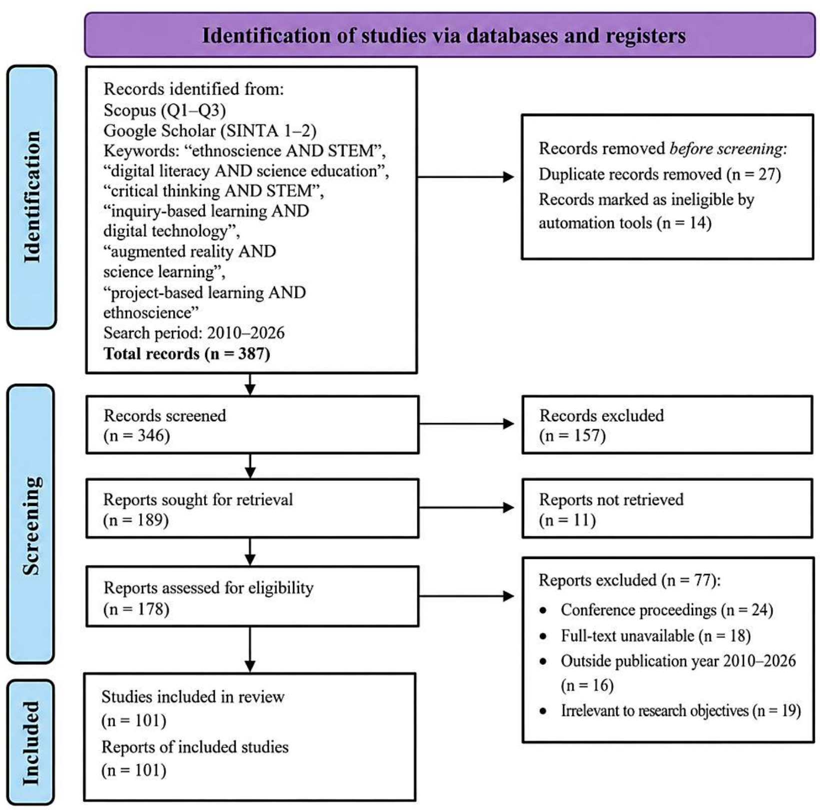

Figure 1. PRISMA flow diagram for article selection

Following the PRISMA-based article selection process presented in Figure 1, a Sankey diagram was constructed to provide a more detailed visualization of the literature screening and thematic distribution of the selected studies. Unlike the PRISMA flowchart, which summarizes the sequential filtering process, the Sankey diagram illustrates how the initially identified publications were progressively refined into the final dataset and categorized according to the major research themes. This complementary visualization offers a clearer representation of the review process while highlighting the thematic composition of the 101 articles in the analysis.

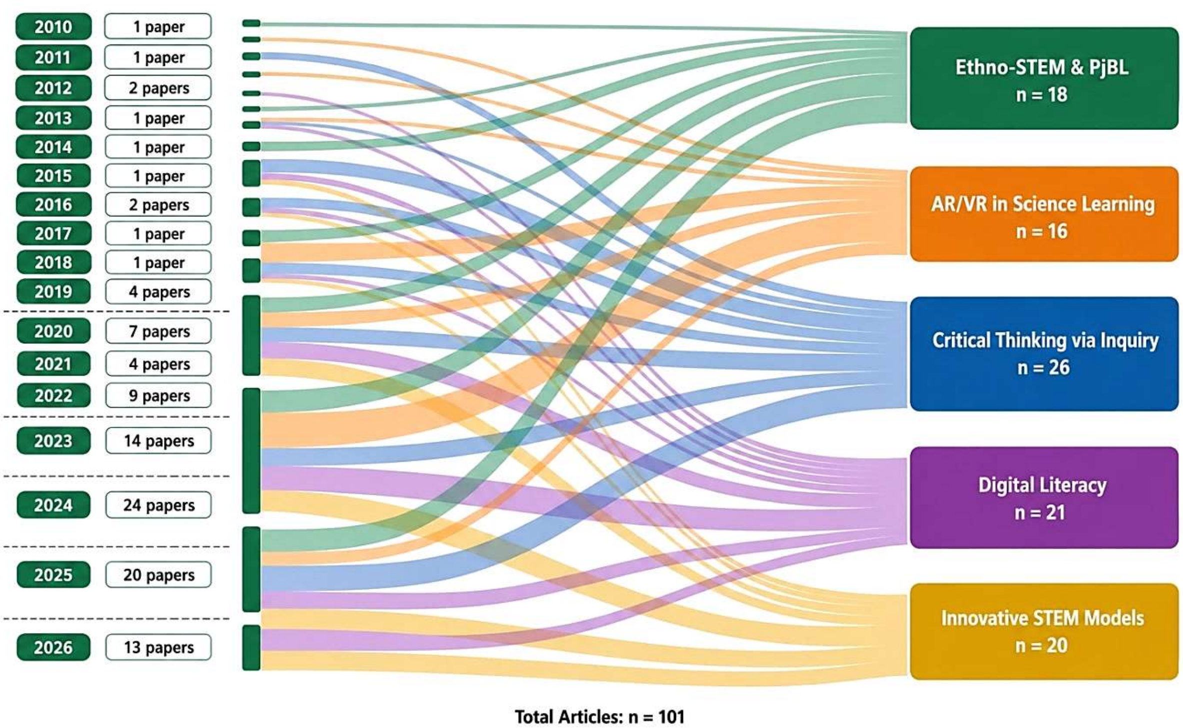

Figure 2. Sankey diagram of review articles by year and theme

Quality Assessment

To ensure that the 101 articles retained for in-depth analysis possessed adequate methodological rigor, a structured quality appraisal was integrated into the eligibility stage of the PRISMA process. Given the methodological diversity of the corpus, comprising quasi-experimental, survey-based, qualitative, and mixed-methods studies, the Mixed Methods Appraisal Tool (MMAT, 2018 version) was employed, as it enables a single, consistent appraisal framework across heterogeneous study designs (Hong et al., 2018). Two reviewers independently rated each article against the two MMAT screening questions (clarity of the research question and adequacy of the data collected to address it) and the five criteria corresponding to its study-design category (e.g., appropriateness of the sampling strategy and instrument validity for quantitative studies; coherence between data sources, collection, and analysis for qualitative studies; adequacy of the integration procedure for mixed-methods studies). Articles were retained only if they satisfied both screening questions and met at least three of the five relevant criteria; discrepancies between reviewers were resolved through discussion until consensus was reached. Articles that failed to meet this threshold, most commonly due to insufficient reporting of sampling procedures, instrument validity/reliability, or data-analysis transparency, were excluded together with the other articles removed at the eligibility stage. The 101 articles retained for thematic and bibliometric analysis each satisfied at least three of the five applicable MMAT criteria, indicating an overall moderate-to-high level of methodological rigor across the reviewed corpus.

Data Analysis

Data were analyzed using thematic analysis and narrative synthesis approaches, following an inductive, three-stage coding procedure informed by Braun and Clarke's (2006) thematic analysis framework and Strauss and Corbin's (1998) coding logic. First, during open coding, the full text (methods, results, and discussion sections) of each of the 101 articles was read repeatedly by two reviewers, who inductively assigned initial descriptive codes to segments referring to interventions, technologies, theoretical constructs, and outcome variables (e.g., "AR-assisted simulation", "local-wisdom-based worksheet", "N-gain in critical thinking", "digital literacy indicator"). Each code was logged in a coding matrix together with the article ID, the supporting excerpt, and a brief memo, yielding an initial set of low-level descriptive codes. Second, during axial coding, semantically related codes were grouped into broader conceptual categories by examining recurring relationships between conditions (e.g., type of intervention or technology), context (educational level, subject area), and outcomes (critical thinking, digital literacy, creativity, motivation); overlapping or redundant codes were merged, and the resulting categories were cross-checked against the keyword co-occurrence clusters produced by the VOSviewer bibliometric mapping (232 items, 5 clusters; see the following subsection) to triangulate the qualitative categorization with the quantitative keyword network. Third, during selective coding and theme formulation, the axial categories were iteratively compared, consolidated, and refined by both reviewers through a constant-comparison process until a stable, non-overlapping set of themes emerged that best represented the pedagogical and technological focus of the corpus; disagreements in category boundaries were resolved through discussion and, where necessary, re-reading of the original articles.

This process yielded five dominant themes reported in the Results section: (1) Ethno-STEM and Project-Based Learning; (2) Augmented Reality and Virtual Reality in Science Learning; (3) Critical Thinking Skills through Inquiry in Science; (4) Digital Literacy in Education; and (5) Innovative STEM Learning Models. Each article was assigned to a single primary theme based on its dominant focus, with secondary foci noted in the coding matrix where relevant. Each article was categorized based on its primary theme, research method, examined variables, and key findings. Bibliometric analysis was conducted using VOSviewer version 1.6.20 to map the relationships between keywords across all selected articles, producing a network map of 232 items in 5 clusters with a total link strength of 67,222. The distribution of articles by theme and journal source is presented in Table 2.

Table 2. Distribution of articles by theme and journal source

No.	Them	Scopus	SINTA	Total Articles
1	Ethno-STEM and Project-Based Learning	12	6	18
2	Augmented/Virtual Reality in Science	11	5	16
3	Critical Thinking through Inquiry	18	8	26
4	Digital Literacy in Education	14	7	21
5	Innovative STEM Learning Models	13	7	20
	Total	68	33	101

To improve theoretical consistency across heterogeneous studies, the synthesis of critical thinking findings was guided by Facione's Delphi framework (1990). Reported learning outcomes from each study were interpreted according to six cognitive dimensions: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Studies using alternative critical thinking instruments were mapped onto these conceptual dimensions whenever possible, enabling a comparable synthesis despite methodological differences.

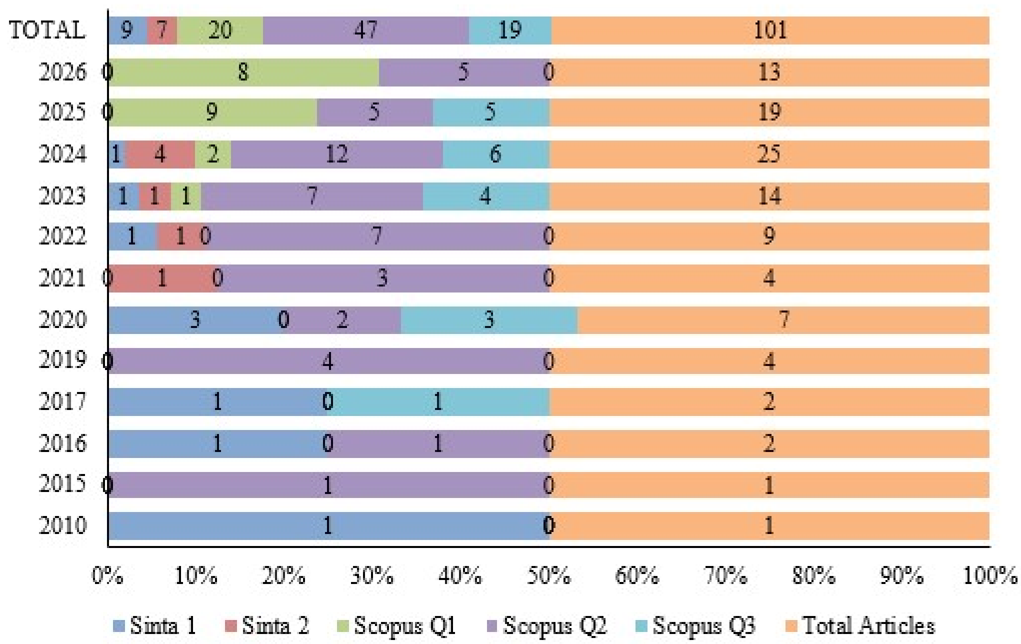

Figure 3. Stacked bar diagram 10% distribution of articles by year

As presented in Figure 3, the distribution of the 101 reviewed articles across accreditation categories reveals a marked temporal shift in the scholarly indexing landscape underpinning this body of literature. Publications indexed in Scopus (Q1–Q3) constitute the dominant proportion of the corpus (85.1%, n = 86), substantially outweighing those indexed solely in Sinta (15.8%, n = 16), a pattern that becomes increasingly pronounced from 2021 onward, culminating in the complete absence of Sinta-indexed sources in 2025 and 2026. It is worth noting that the sum of the Sinta and Scopus subtotals (16 + 86 = 102) exceeds the total number of unique articles (n = 101) by one; this discrepancy is attributable to a single article that was concurrently accredited under both Sinta and Scopus indexing systems and was therefore counted in both categories, rather than reflecting an error in data tabulation. When examined longitudinally, the proportional trend further indicates a qualitative maturation of the reviewed literature, characterized by an early reliance on nationally indexed (Sinta 1–2) and mid-tier internationally indexed (Scopus Q2–Q3) journals between 2010 and 2020, followed by a pronounced escalation in Scopus Q1 representation from 2023 (7.1%) to 2026 (61.5%). This upward trajectory suggests a growing emphasis among researchers in this field on disseminating findings through higher-impact, internationally recognized outlets, thereby reflecting broader shifts in publication strategy and quality standards within the discipline over the past decade.

RESULT AND DISCUSSION

What are the Research Trends in Ethnoscience, Digital Technology, Inquiry, Digital Literacy, and Critical Thinking in STEM Education?

This section examines global research trends and thematic developments related to ethnoscience, digital technology, inquiry, digital literacy, and critical thinking in STEM education, using bibliometric mapping and systematic literature synthesis.

To provide a comprehensive overview of the reviewed studies, Table 3 presents a synthesis matrix summarizing the research design, intervention or technology, dependent variables, and key findings of the selected literature. This matrix serves as the foundation for the thematic discussion presented in subsequent subsections.

Table 3. Synthesis matrix of the reviewed literature

Research Focus	Representative Studies	Main Intervention	Main Findings
Ethno-STEM and Project-Based Learning	Sumarni and Kadarwati (2020); Atmojo et al. (2025); Jufrida et al. (2024)	Ethno-STEM PBL, local-wisdom-based learning	Improved critical thinking, creativity, scientific literacy, and cultural literacy.
Augmented Reality in Science Learning	Pamorti et al. (2024); Qumillaila et al. (2017); Ng et al. (2024)	AR-based learning media and digital storytelling	Enhanced conceptual understanding, engagement, critical thinking, and digital creativity.
Virtual Reality in Science Learning	Widiyatmoko et al. (2023); Luo et al. (2025)	VR game-based learning and virtual simulation	Improved STEM literacy, motivation, creativity, and problem-solving skills.
Inquiry and Critical Thinking	Adhelacahya et al. (2023); Ramlawati et al. (2025); Kaçar and Balim (2021)	PBL, differentiated science inquiry, argument-driven inquiry	Consistent gains in critical thinking, science process skills, and conceptual understanding.
Digital Literacy in Education	Stefany and Helmi (2024); Harlanu et al. (2023); Jiang and Gu (2025)	Digital literacy development, instrument validation, GenAI-assisted learning	Strengthened digital literacy competencies and critical digital literacy awareness.
Innovative STEM Learning Models	Arlinwibowo et al. (2023); Wibawa et al. (2024); Tabakova-Komsalova et al. (2024)	Gamification, interactive PBL media, AI-integrated STEM	Increased motivation, engagement, computational thinking, and interdisciplinary STEM skills.

Global publication trends: analysis of dimensions AI data

Before presenting the findings by theme, it is important to understand the global research landscape in this field through bibliometric data from Dimensions AI. A search employing the criteria ‘ethnoscience, digital technology, and inquiry-based learning in STEM education’ yielded a total of 4,095 publications from 2017 to 2026 (Figure 4). These data provide a macro-level context for the 101 articles subjected to in-depth analysis in the present study.

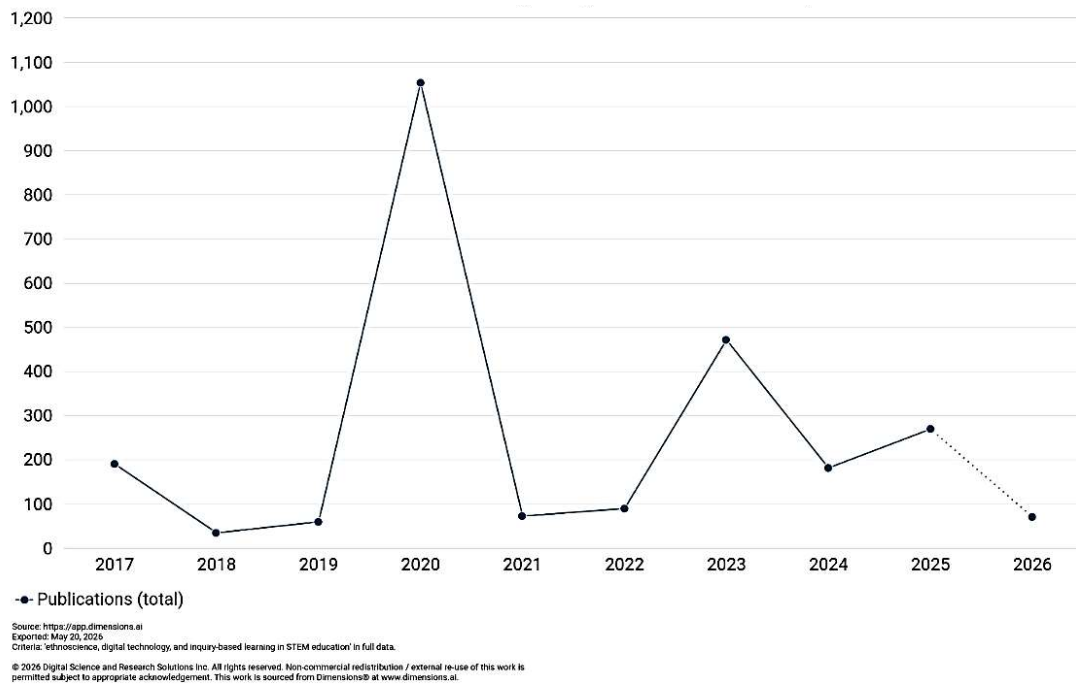

Figure 4. Annual publication trends (dimensions ai, 2017–2026): criteria: 'ethnoscience, digital technology, and inquiry-based learning in STEM education'

Figure 4 reveals a notable trend: an extraordinary surge in publications occurred in 2020 (1,053 articles), most likely triggered by the COVID-19 pandemic, which accelerated the adoption of digital technology in education on a global scale. This phenomenon is consistent with the findings regarding the acceleration of learning digitalization in the post-pandemic period (Sundgren et al., 2023), as well as with the review by Hinostroza et al. (2024), which documented the massive growth of digital technology research in scientific inquiry. Following a decline in 2021–2022, a significant increase occurred again in 2023 (471 articles) and continued through to 2025 (269 articles), indicating that research interest in this topic continues to grow consistently. This pattern aligns with the study by Prananta et al. (2024), which specifically documented the exponential growth of AR research in science education (Amanah et al., 2026; Amanah et al., 2025; Amanah et al., 2022).

VOSviewer Bibliometric Mapping: Theme Clusters and Keyword Networks

Bibliometric analysis using VOSviewer version 1.6.20 produced a comprehensive keyword network map derived from all 101 selected articles. The mapping yielded 232 items (keywords), 12,033 links, and a total link strength of 67,222, organized into 6 distinctive thematic clusters (Figures 5 and 7).

The five clusters identified in Figure 5 represent the primary research domains that constitute the landscape of this study, namely: (1) Red Cluster: Science Education Research and Trends (science education, article, publication, STEM education, meta-analysis, research trend); (2) Yellow Cluster: Interdisciplinary Contexts (mathematics education, biology, mathematics, physics education, pedagogy) (item perception, ethnoscience learning, digital teaching material); (3) Purple Cluster: Perceptions and Ethnoscience (item perception, ethnoscience learning, digital teaching material); (4) Green Cluster: Teaching

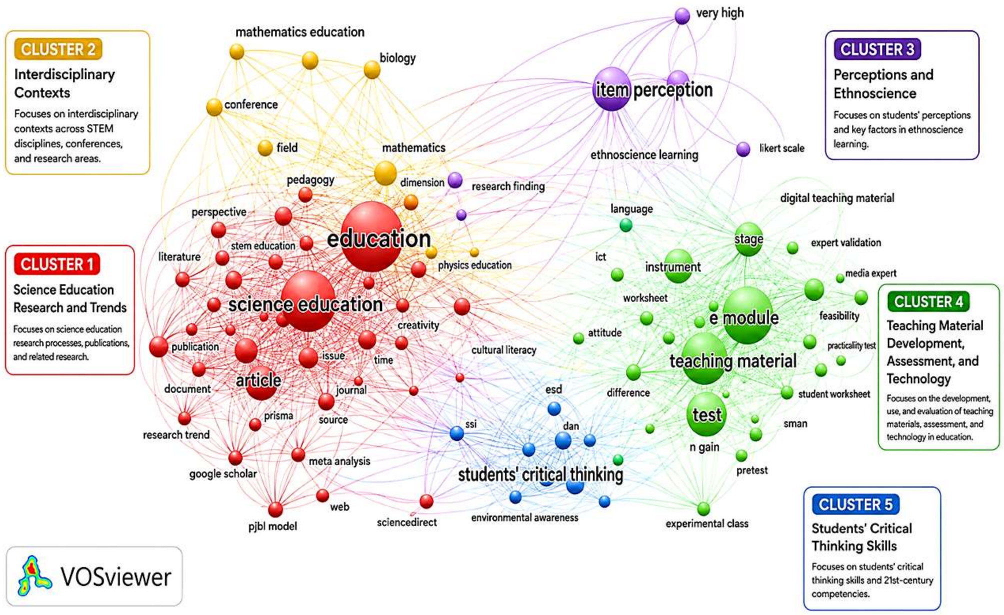

Figure 5. VOSviewer network visualization: keyword network map of 101 articles (232 items, 5 clusters)

Material Development, Assessment, and Technology (teaching material, e-module, test, instrument, student worksheet, N-gain, experimental class, feasibility) and (5) Blue Cluster: Students' Critical Thinking Skills (ESD, SSI, ICT, environmental awareness).

The dominance of the green cluster (teaching material development, assessment, and technology) and the red cluster (science education research and trends) confirms that the majority of research remains focused on the development of partial learning products, rather than on integrated learning models that simultaneously incorporate ethnoscience, digital inquiry, and STEM. This reinforces the identification of the gap that underpins the innovative learning model framework. Researchers have respectively examined discovery-based multi-representation approaches as examples of efforts to address this gap (Chusni, 2023; Amanah et al., 2025).

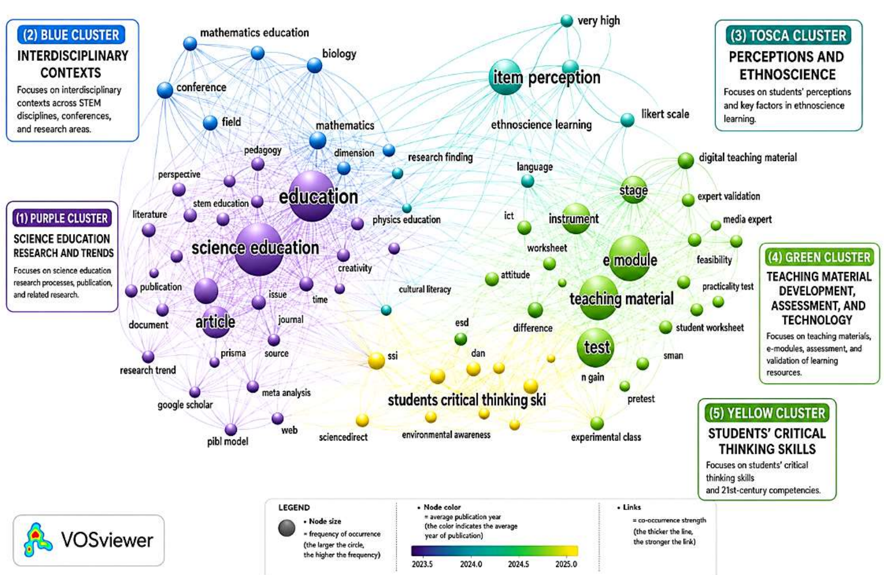

Figure 6. VOSviewer overlay visualization: temporal trends per cluster (yellow = more recent, 2024–2025; dark blue = older, 2023)

The Overlay Visualization in Figure 6 reveals the temporal dimension of the research: keywords in yellow (brighter) represent more recent topics (2024–2025), while dark blue indicates more established topics. It is evident that keywords such as 'web', 'N-gain', 'SSI', and 'PJBL model' are experiencing rapid growth over the past two years. Conversely, concepts such as 'science education', 'teaching material', and 'e-module' have long been a primary research focus. This pattern is consistent with the findings of Sogalrey et al. (2024), who reported that digital literacy research in education reached its peak in 2023.

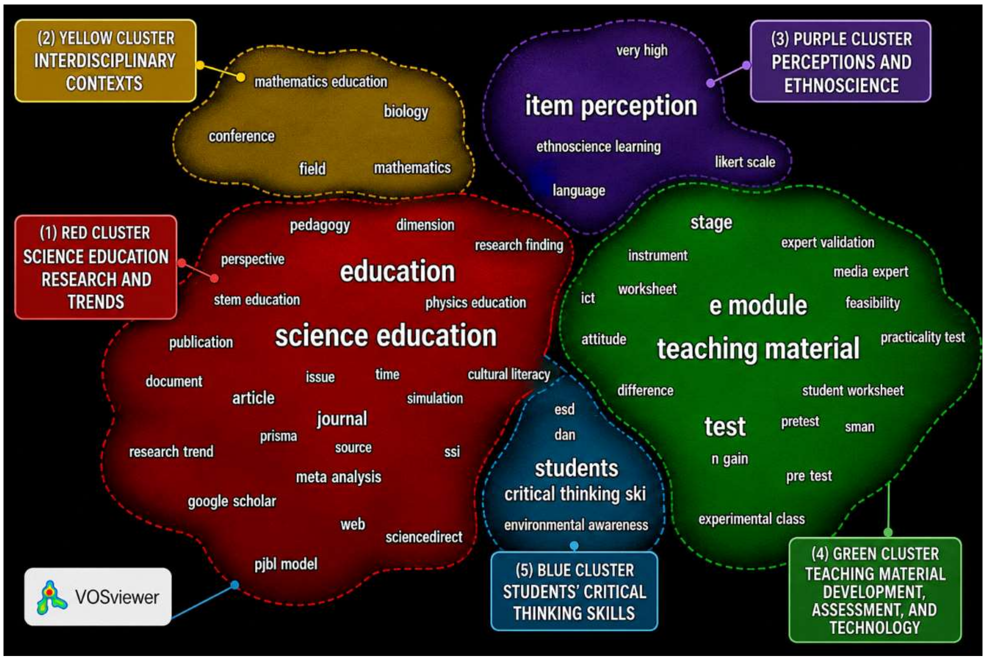

Figure 7. VOSviewer density visualization: concentration of research activity per keyword cluster

The Density Visualization (Figure 7) illustrates the concentration of research activity: the areas with the brightest colors (green-yellow) indicate the most active zones, namely 'science education', 'teaching material', 'e-module', and 'students' critical thinking skills'. This visualization confirms that although critical thinking skills constitute a highly active research topic, the comprehensive integration with ethnoscience and digital inquiry remains in a darker zone (less active), indicating considerable potential for future research.

Which Learning Models are Effective in Developing Critical Thinking and Digital Literacy?

This section synthesizes empirical evidence on the effectiveness of various learning models in fostering students' critical thinking and digital literacy across diverse STEM learning contexts.

Theme 1: Ethno-STEM and project-based learning

1. Project and learning design studies

Of the 18 articles examined under this theme, there is a strong consensus that integrating ethnoscience within a project-based learning (PjBL) approach yields a significant positive impact on students' critical and creative thinking skills. Sumarni & Kadarwati (2020), in their study employing a pre-experimental design with 230 students from seven senior secondary schools in Central Java, demonstrated that Ethno-STEM PjBL effectively enhances critical and creative thinking skills, with 22.6% of students achieving the high category for critical thinking and 27.4%

for creative thinking. Similar results were reported by Juniawan et al. (2024), who developed Ethno-STEM digital teaching materials for elementary school students using the ADDIE model, achieving a feasibility rate of 92.42% and an N-gain of 0.40, alongside positive responses from students (90.35%) and teachers (90.62%).

Atmojo et al. (2025) extended this inquiry by affirming the role of ethnoscience in simultaneously developing critical thinking and cultural literacy, thereby establishing culture-STEM integration as an increasingly relevant research agenda. Rosyidah et al. (2025), through a systematic review, demonstrated that local wisdom in STEM is not only relevant to SDG-4 (quality education), but also strengthens meaningful contextual learning for students. Ainur et al. (2025) specifically demonstrated that ethnoscience augmented with virtual physics simulations and AR enhances students' creativity and learning motivation, a finding highly relevant to the design of an innovative learning model.

At the elementary school level, Rahmat et al. (2023) demonstrated that the use of traditional musical instruments in science learning improves students' critical thinking, affirming the relevance of local wisdom across educational levels. The findings of Tohri et al. (2022) concerning the urgency of character education grounded in Sasak local wisdom in East Lombok add a character dimension to the ethnoscience-STEM agenda that warrants consideration in the design of an innovative learning model.

Jufrida et al. (2024) reported that the implementation of ethnoscience-based learning at the junior secondary level demonstrably enhances scientific literacy. However, it continues to require adequate teacher competence support (Suwandi et al., 2025). This limitation is reinforced by data from Farihah et al. (2025), which reveals that 100% of KSSM teachers in Malaysia require practical game-based STEM modules accompanied by implementation guidelines. These findings affirm that the integration of ethnoscience within PjBL-STEM is not merely a cultural ornamental addition, but rather an epistemological component that strengthens the foundations of learning, with the caveat that teachers require adequate professional support.

2. Measurement instrument development

Unlike the studies above, one article in this theme focuses on building a measurement tool rather than testing a learning intervention. Assessment of problem-solving skills for preservice teachers is important in science instruction. The purpose of this study is to discover: (a) the characteristics of the Problem-Solving Essay Test Instrument (PSETI); (b) How is the validity based on expert assessment; (c) how validity and reliability are based on trials. The research method is research and development. The study covers three stages: (1) planning the test, (2) trying out the test, and (3) determining the validity and reliability. The sample of this study was 80 preservice elementary school teachers of basic science concepts. The PSETI is in the form of an essay test, consisting of 19 items. The essay test contains ethnoscience problems. Content validity, based on the Aiken index, is 0.84, indicating good validity. The results of the development of the PSETI instrument show that 19 items met the validity and reliability criteria of the 21 items/ compiled. The PSETI is an essay test with scoring that uses a partial credit model based on the three categories in the polytomous data. Instrument reliability was 0.77, and it was concluded that the instrument was good for measuring problem-solving skills of preservice teachers in a science learning context (ethnoscience). Winarto et al. (2022) further developed an ethnoscience-based test instrument (Problem-Solving Essay Test Instrument/PSETI) that demonstrated validity for measuring problem-solving skills within the STEM context.

Together, these articles show two different kinds of contribution. Most studies design and test a learning intervention (a project, teaching material, or module) and report whether it improves outcomes such as N-gain or feasibility. One study instead builds a measurement tool: a validated instrument that other researchers can use to assess problem-solving skills. In short, design studies show what works, while instrument studies provide the tools to measure it. Since only one article in this theme develops such a tool, future Ethno-STEM PjBL research would benefit from more validated, context-specific instruments, rather than relying mainly on generic critical-thinking tests.

Theme 2: Augmented reality and virtual reality in science learning

1. Augmented reality in STEM learning

Augmented Reality (AR) has emerged as an effective technology for contextualizing STEM learning by overlaying virtual objects onto real-world environments. The reviewed studies consistently demonstrate that AR enhances students' conceptual understanding, engagement, and inquiry processes by facilitating real-time visualization of abstract scientific phenomena and maintaining connections with authentic cultural and environmental contexts. Within ethnoscience-based learning, AR facilitates the representation of local wisdom through interactive digital visualization, allowing students to investigate scientific concepts embedded in cultural practices without disconnecting them from their original contexts. Furthermore, AR-supported inquiry activities encourage observation, evidence collection, and hypothesis generation, thereby contributing to the development of critical thinking and digital literacy. However, several studies also report limitations related to instructional design quality, teacher digital competence, and device accessibility, which continue to influence the effectiveness of AR implementation.

2. Virtual reality in STEM learning

Virtual Reality (VR) provides fully immersive learning environments that enable students to explore scientific concepts beyond the limitations of conventional classrooms. The reviewed literature indicates that VR is particularly effective for visualizing complex, microscopic, hazardous, or inaccessible scientific phenomena through interactive simulations. In inquiry-based STEM education, VR promotes experimentation, scientific reasoning, and problem-solving by allowing learners to manipulate variables and observe immediate consequences within simulated environments. Compared with AR, VR offers a higher level of immersion, which can increase learning motivation and conceptual understanding. Nevertheless, the reviewed studies also highlight several challenges, including higher cognitive load, increased hardware requirements, cybersickness risks, and the need for carefully designed instructional scaffolding to prevent students from becoming cognitively overloaded during inquiry activities.

3. Augmented reality: literature synthesis

A total of nine articles in the reviewed corpus specifically examined the effectiveness of AR technology in science learning, and their findings converge on a consistent pattern of significant benefits. Prananta et al. (2024), through a bibliometric analysis of 3,386 publications (2015–2024), documented the exponential growth in the use of AR in science, with a peak in 2023, consistent with Dimensions AI data. Pamorti et al. (2024) demonstrated the effectiveness of AR-based media in enhancing critical thinking skills in IPAS (Natural and Social Sciences) subject matter, reporting a within-study N-Gain of 56.52% with a significance value of 0.000, indicating a statistically significant improvement relative to its own control group. In the context of physical education, Muktiani et al. (2022) similarly demonstrated that AR-based mobile applications effectively improved student learning outcomes ($p = 0.000 < 0.05$) for Pencak Silat material. Qumillaila et al. (2017) earlier developed Android-based AR for the human excretory system with positive student responses, establishing one of the earliest precedents for the use of smartphone-based AR in science learning in Indonesia. Ng et al. (2024) explored the use of CoSpaces in the creation of AR digital stories, identifying its potential as a creative platform that promotes digital literacy and design thinking. Code et al. (2026) further showed that game-based AR inquiry activities promoted higher expressions of learner agency (self-directedness) among students. Prahani et al. (2022), through a bibliometric analysis of publications from 2002–2021, affirmed that AR has experienced rapid growth in physics learning and is more flexible in implementation than VR, particularly in school settings with infrastructural limitations.

Taken together, the AR literature converges on a consistent instructional profile: AR functions primarily as a contextual-augmentation tool that overlays digital information onto real-world observation, which keeps its cognitive demands comparatively low and makes it particularly well suited to integrating ethnoscience and local cultural content into inquiry-based learning. Its main limitations lie not in cognitive load but in instructional design quality, teacher digital competence, and device accessibility.

4. Virtual reality: literature synthesis

Fewer articles in the corpus focused specifically on VR, but their findings are equally consistent. Widiyatmoko et al. (2023) demonstrated that Virtual Reality Game-Based Learning (VRGBL) significantly enhanced students' STEM literacy, with the experimental group achieving an N-Gain of 0.57 (moderate category) compared with 0.28 for conventional learning within the same study; the largest within-study gain was recorded for scientific literacy, at an N-Gain of 0.73. Luo et al. (2025) demonstrated that museum-based virtual simulations enhanced multidisciplinary knowledge acquisition, learning motivation, critical thinking, creativity, and problem-solving in the C-STEAM context. Prahani et al. (2022) additionally reported that, across the 2002–2021 period, VR was quantitatively the more dominant technology in physics-education publications, even though AR proved more flexible to implement.

Read together, the VR literature indicates that VR's distinctive strength is full immersion: it allows learners to investigate scientific phenomena that are microscopic, hazardous, or otherwise inaccessible through direct observation, which appears to translate into strong gains in STEM and scientific literacy. This immersive advantage, however, comes with a correspondingly higher cognitive and technical cost: the reviewed studies point to greater hardware requirements, cybersickness risk, and a need for carefully designed instructional scaffolding to prevent cognitive overload during inquiry activities.

5. Comparative synthesis: effectiveness mapping of AR versus VR

Because Pamorti et al. (2024) and Widiyatmoko et al. (2023) report gains on different scoring bases (a raw percentage gain versus a normalized N-Gain index), their figures are not directly comparable in magnitude. Read together, however, both strands of evidence point to a consistent pattern: technology-based media, whether AR or VR, tend to outperform conventional-learning comparisons within their own studies, rather than indicating that one technology produces a categorically larger effect than the other.

What differentiates the two technologies is not the size of their effect but the instructional mechanism through which that effect is produced. AR supports contextual inquiry by enriching real-world observation with digital information layered onto authentic settings, imposes comparatively lower cognitive demands, and is therefore particularly suitable for integrating ethnoscience and local cultural knowledge into STEM learning. VR, in contrast, supports immersive simulation, enabling learners to investigate phenomena that are difficult or impossible to observe directly, but requires more intensive instructional scaffolding to manage the higher cognitive load and technical demands (e.g., device requirements, cybersickness) associated with full immersion. Mapped onto research design, this distinction implies that AR is the more readily deployable option in infrastructurally limited or culturally grounded learning contexts. In contrast, VR is better positioned for phenomena that cannot be safely, ethically, or practically observed in the physical classroom.

Theme 3: critical thinking skills through Inquiry in science

The findings presented in this section are interpreted through Facione's (1990) critical thinking framework. Across the reviewed studies, improvements in critical thinking were reflected through various combinations of interpretation, analytical reasoning, evidence evaluation, inference, explanation, and reflective judgment. However, individual studies frequently emphasized different indicators depending on their instructional context and assessment instruments. This theme attracted the greatest research interest, with 26 selected articles. The findings consistently demonstrate that inquiry-based approaches (in their various forms) constitute the most effective strategy for enhancing students' critical thinking skills. Adhelacahya et al. (2023) demonstrated that an electronic module based on PBL-STEM yielded an N-gain of 0.76 (high category) for critical thinking among students at SMAN 1 Pacitan. PBL transforms problems into opportunities for critical thinking (Shylvia et al., 2025). Usman et al. (2023), in the Nigerian context, showed that STEM-PBL significantly improved the academic achievement of biology students on the concepts of diffusion and osmosis.

Ramlawati et al. (2025) introduced an innovative DSI model grounded in TaRL (Teaching at the Right Level), which combines differentiated learning with inquiry. The results were highly promising: students' critical thinking skills improved with an N-Gain of 0.47 in the experimental group versus 0.35 in the control group, and science process skills also improved significantly. This research is particularly relevant as it demonstrates that higher levels of inquiry (self-directed inquiry) correspond to greater improvements in student ability.

Kaçar & Balim (2021), through the Argument-Driven Inquiry (ADI) method in physics learning, demonstrated that argumentation-based inquiry yielded significantly greater improvements in conceptual understanding compared to conventional learning. Akhdinirwanto et al. (2020) developed a PBL model incorporating argumentation as a hypothetical model for enhancing critical thinking skills among junior secondary students, emphasizing the role of argumentation as cognitive scaffolding. Abdurrahman et al. (2019) confirmed that a multiple representation-based worksheet produced an N-Gain of 0.34 (moderate category) in critical thinking skills, with the 'basic explanation' indicator showing the greatest improvement (0.51).

Jegstad et al. (2025), through a systematic review, identified three dominant approaches to critical thinking in primary school classrooms: the disposition approach, cognitive skills, and reflective practice (all of which may be integrated within a digital inquiry model). Oscar and Ana (2026) reinforced these findings by demonstrating that ICT-based pedagogical mediation effectively develops critical thinking in primary education through technology-assisted inquiry. Shahab and Barak (2026) identified the pedagogical practices and modes of engagement most effective for developing critical thinking in higher education, emphasizing the importance of a dialogic learning environment.

From the perspective of project-based inquiry, Han et al. (2016) demonstrated the positive effects of STEM PBL on four mathematics topics, while Bara and Xhomara (2020) confirmed the superiority of student-centered PBL-based learning over conventional approaches in science academic achievement. Muhfahroyin et al. (2023) developed an integrated TPS-PBL approach to improve critical thinking among low-ability students, while Rijal et al. (2021) documented variations in the effect based on prior ability levels. Suningsih et al. (2025) specifically mapped the critical thinking levels of junior secondary students in geometry problem-solving using the TEM Journal approach, finding that only a small proportion of students achieved the highest level.

Although inquiry-based learning has consistently been recognized as an effective approach for promoting scientific reasoning and conceptual understanding, recent evidence suggests that its impact may be limited when inquiry activities are implemented as short-term, teacher-guided investigations that primarily focus on hypothesis testing and concept acquisition. Such approaches often provide fewer opportunities for sustained collaboration, authentic problem-solving, iterative design, and the meaningful use of digital technologies. In contrast, Project-Based Learning (PBL) extends the inquiry cycle by engaging students in long-term investigations centered on authentic problems that require integrating scientific knowledge, engineering design, and digital tools to produce tangible solutions or products. Recent systematic reviews indicate that project-based inquiry creates richer learning experiences by fostering continuous reflection, collaborative decision-making, and interdisciplinary knowledge construction, thereby producing stronger gains in critical thinking, problem-solving, and digital literacy than conventional inquiry implemented in isolation (Loyens et al., 2023; Tafakur et al., 2023; Guo et al., 2020).

The findings of this review are consistent with recent evidence showing that inquiry serves as the cognitive foundation of scientific investigation. In contrast, PBL strengthens inquiry by embedding it within authentic, collaborative, and technology-rich learning experiences. Consequently, STEM-integrated PBL not only facilitates scientific inquiry but also enables students to apply critical thinking in solving real-world problems, evaluate multiple sources of digital information, and construct evidence-based solutions. These characteristics explain why project-based inquiry demonstrates greater potential for simultaneously developing critical thinking and digital literacy than conventional inquiry-oriented instruction.

The findings from these 26 articles affirm that effective inquiry is not solely about scientific procedures, but about appropriate cognitive scaffolding, deep reflection, and authentic contextualization of problems. Szalay et al. (2025), in a three-year longitudinal study, demonstrated that guided inquiry exerted a small effect on experimental design skills ($d = 0.16$) but at the cost of conceptual mastery, indicating that inquiry must be combined with explicit conceptual reinforcement. The finding by Premthaisong and Srisawasdi (2024) that technology-assisted active inquiry transformed primary school students' conceptions of science learning in a more constructivist direction underscores the urgency of technology integration in modern inquiry models.

Although the reviewed studies employed different instruments to measure critical thinking, most reported outcomes can be interpreted within Facione's six-dimensional framework. The greatest improvements were generally observed

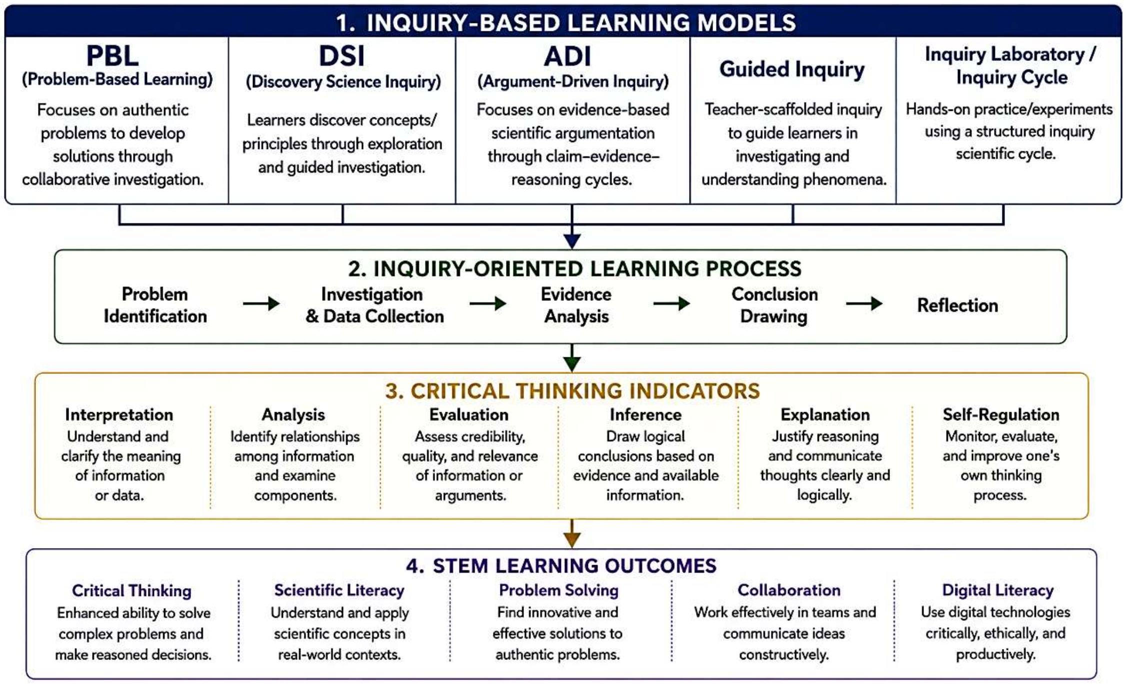

Figure 8. Thematic map: inquiry-based learning models and critical thinking in STEM education

in analytical reasoning, evaluation, and inference during inquiry-based and problem-based learning activities, whereas reflective self-regulation was less frequently assessed. This finding indicates that existing research has predominantly emphasized cognitive performance while giving comparatively limited attention to metacognitive regulation, suggesting an important direction for future instructional model development.

Theme 4: digital literacy in education

Of the 21 articles examined, digital literacy is demonstrated to be a key 21st-century competency that must be developed in an integrated manner within learning. Because the meaning and predictors of digital literacy differ substantially depending on who is being studied, the findings under this theme are organized through a sub-group analysis based on educational level and user demographic: (1) students and learners, (2) teachers and lecturers, (3) parents and older adults outside the formal education system, and (4) cross-national and bibliometric trends. This grouping clarifies that "digital literacy" is not a single uniform construct, but instead shows distinct patterns across populations.

1. Digital literacy among students and learners

At the student level, research emphasizes measurable instruments and the internal or contextual factors that predict digital competence. Harlanu et al. (2023) developed a digital skills literacy instrument that was shown to be valid and reliable (Cronbach's á = 0.943) for measuring students' digital competencies. Ririen and Heriasman (2021) demonstrated the significant influence of self-management on students' digital literacy in Riau, indicating that individual internal factors play an important role. Imjai et al. (2024) demonstrated that digital literacy and logical thinking together predict the internship effectiveness of Generation Z accounting students in Thailand. Gusli et al. (2025), through a meta-analysis of 8 studies, demonstrated that integrating technology into learning improves digital literacy among *madrasah* students, with an effect size of

0.576 (58%), and leadership as a crucial moderating factor. Fang et al. (2025), through unconditional quantile regression analysis, identified gender disparities in digital literacy among students across four European countries, a finding relevant to digital inclusivity policy. Collectively, these studies show that student digital literacy is shaped by individual dispositions (self-management, logical thinking), institutional leadership, and demographic factors such as gender, rather than by technology access alone.

2. Digital literacy among teachers and lecturers

At the educator level, the literature reveals a recurring gap between teachers' positive perceptions of digital literacy and their actual technical competence. Rusydiyah et al. (2020) indicated that prospective teachers hold positive perceptions toward digital literacy; however, computational thinking remained low (48.6%), a gap that requires bridging. Ibda et al. (2023), through a systematic review, found that the digital literacy competencies of elementary school teachers remain variable and require structured improvement. At the higher-education level, Stefany and Helmi (2024), in the Indonesian context, demonstrated a strong relationship between lecturers' digital literacy and the quality of online course design ($r = 0.765$, $p < 0.001$), with digital literacy competence contributing 58.6% to learning quality. More recent studies point toward pedagogical innovation as a response to this gap: Wang and Xu (2026) explored an algorithm-aware writing approach for developing critical digital literacy in the EAP context, while Jiang and Gu (2025) investigated the role of GenAI in supporting a teacher's critical digital literacy through multimodal composition. This pattern suggests that, unlike students, teachers and lecturers are studied primarily in terms of the downstream effect of their own digital literacy on teaching quality, and the strategies used to close their competency gaps.

3. Digital literacy beyond formal education: parents and older adults

A smaller but distinct body of research extends digital literacy beyond the classroom to the family and community ecosystem. Choi et al. (2023) developed a validated Everyday Digital Literacy Questionnaire for older adults, extending the scope of digital literacy beyond the formal educational context. Utami et al. (2022) affirmed the urgency of digital literacy for parents in educating children in the digital era, an ecosystem dimension that is frequently overlooked in school-centered studies. At a broader societal level, Ika et al. (2024) examined the strengthening of digital literacy in Indonesia through the pillars of collaboration, innovation, and sustainability education, affirming that digital literacy extends beyond mere technical skills to encompass values and character (Akmar et al., 2026; Amanah et al., 2025; Amanah et al., 2025a). Compared to the student- and teacher-focused literature, studies in this group treat digital literacy less as a measurable skill and more as a lifelong, intergenerational, and values-based competency.

4. Cross-national and bibliometric trends

At the macro level, Sogalrey et al. (2024), through a bibliometric analysis of 2,169 Scopus publications (2015–2024), documented significant growth in digital literacy research, with a peak in 2023 and the United States as the primary contributor, followed by Indonesia, consistent with Dimensions AI data indicating 269 publications in 2025. This bibliometric pattern indicates that, although research volume is increasing globally, the substantive focus still varies widely across the demographic sub-groups above rather than converging on a single, unified conception of digital literacy.

Taken together, this sub-group analysis shows that digital literacy research does not describe one homogeneous phenomenon. Studies on students concentrate on measurable instruments and individual or institutional predictors; studies on teachers and lecturers foreground the gap between perceived and actual competence and its downstream effect on teaching quality; and studies on parents and older adults reposition digital literacy as an ecosystem-level, values-based competency rather than a technical skill. Future research would benefit from comparative, cross-group designs that directly examine how digital literacy patterns transfer (or fail to transfer) between students, educators, and the wider family and community context.

Theme 5: innovative STEM learning models

Of the 20 articles examined, a variety of innovative STEM learning models have been developed and tested. Arlinwibowo et al. (2023) examined gamification in STEM and demonstrated its potential for enhancing student engagement (Rokhmat et al., 2025), while Farihah et al. (2025), through a teacher needs analysis, revealed that 100% of KSSM teachers in Malaysia require practical game-based STEM modules accompanied by implementation guidelines.

Tabakova-Komsalova et al. (2024) introduced the integration of AI (Prolog) in STEM, demonstrating that interdisciplinary learning enhances computational thinking and student motivation. Adekunle dan Basil (2026) developed an AI-supported PBL approach that demonstrably enhanced computational thinking skills in STEM. Mui et al. (2026), through a systematic review, developed a theory of AI literacy grounded in Habermas' three cognitive knowledge interests, providing a robust theoretical framework for the integration of AI in STEM.

Susanta et al. (2025) demonstrated that digital STEAM-inquiry modules effectively improve literacy in both urban and rural elementary schools, although disparities that require addressing persist. Wibawa et al. (2024) developed interactive PBL-based learning videos that enhanced science learning motivation in elementary school, while Puger et al. (2024) developed a metacognition-based learning model that enhances agile innovation and critical thinking. Amri et al. (2024) developed a STEM Learning approach using a simple hydraulic pump project that improved students' communication and collaboration skills.

Behnamnia et al. (2025) examined the relationship between creative thinking and learning outcomes in a digital STEM environment, finding that creativity serves as a mediator between digital engagement and learning achievement. Yang et al. (2025) demonstrated that Makerspace in early childhood education enhances STEM thinking skills and children's emotional development. Thanh et al. (2025), through a bibliometric analysis of STEM in primary schools (2004–2024), identified global research trends and gaps, while Tuyet et al. (2024) examined STEM publications in Southeast Asian countries (2000–2022), revealing significant research disparities between developed and developing nations in the region. These findings highlight the role of innovative STEM approaches in enhancing creativity, STEM thinking, and digital literacy (Maisarah et al., 2022).

Collectively, these studies indicate that no single integrated model yet exists that systematically incorporates ethnoscience, digital inquiry, knowledge reflection, and STEM. This gap serves as the foundation for developing the innovative learning model. Existing models tend to be partial: examining gamification without ethnoscience, or digital inquiry without a local cultural component.

What Research Gaps Underlie the Development of an Innovative Learning Model?

Research gaps and implications

Based on the synthesis of the 101 articles reviewed, reinforced by Dimensions AI data, the article-level coding matrix (Table 2), and VOSviewer mapping, several significant research gaps are identified: No integrated learning model yet exists that explicitly and holistically incorporates ethnoscience, digital inquiry, knowledge reflection, and STEM. Because each of the 101 reviewed articles was coded and assigned to a single dominant theme (Ethno-STEM and PjBL, n = 18; AR/VR, n = 16; Critical Thinking through Inquiry, n = 26; Digital Literacy, n = 21; Innovative STEM Models, n = 20), this single-theme coding scheme could, on its own, mechanically predetermine a "no-integration" outcome; the claim therefore cannot rest on the primary-theme classification alone. To probe this further, the secondary, non-dominant foci that the coding matrix recorded for each article were reviewed individually: across the corpus, these secondary foci recurred almost exclusively within, rather than across, the five themes, and not one article treated ethnoscience, digital inquiry, reflective knowledge, and STEM as co-equal, simultaneously measured constructs. It is this article-level review of secondary foci, rather than the single-theme classification in isolation, that substantiates the fragmentation claim. The VOSviewer keyword network offers a converging, secondary line of evidence (the ethnoscience-digital inquiry-STEM keywords occupy sparsely connected clusters); (2) The majority of studies are partial in nature, examining one or two components in isolation; (3) The Indonesian context, although beginning to receive attention (evidenced by Indonesia's position as the second largest contributor to digital literacy research after the United States, according to Sogalrey et al. (2024)), remains underrepresented in integrated ethnoscience-STEM research; and (4) The aspect of reflective knowledge as a key component in deepening scientific thinking remains insufficiently explored. This gap is directly visible within the Results themselves: across all five themes, reflection was addressed only tangentially and within a single theme: Theme 3 (Critical Thinking Skills through Inquiry), where reflective judgment appeared merely as one interpretive dimension of Facione's framework rather than as an object of empirical measurement, reflective self-regulation was explicitly reported as "less frequently assessed" than the other cognitive dimensions, Jegstad et al. (2025) named reflective practice as only one of three general approaches without further elaboration, and project-based inquiry syntheses referred to "continuous reflection" only as a general benefit rather than a measured construct. No article discussed under Themes 1, 2, 4, or 5 addressed reflective knowledge at all. Beyond the 101 reviewed articles, an emerging line of work on GenAI-assisted reflective thinking (Wei et al., 2025) points to a promising direction. However, it lies outside the primary corpus and has not yet been integrated into ethnoscience-STEM-digital inquiry research.

To substantiate this claim beyond the single-dominant-theme coding scheme used to construct Table 2, a supplementary multi-label coding pass was undertaken: each of the 101 articles was re-examined and credited with every theme it substantively addressed, rather than only its single primary category, across twelve finer-grained analytic codes (Critical Thinking, Digital Literacy, STEM Education, Primary/Elementary Education, Inquiry-Based Learning, Problem-Based Learning, 21st-Century Skills, Ethno-STEM/Local Wisdom, Augmented Reality, Science Process Skills, AI/GenAI, and Gamification/VR/Game-Based Learning). The resulting article-level thematic co-occurrence matrix, visualized as a heatmap (Figure 9), operationalizes thematic integration directly by recording how many articles concurrently address any given pair of themes, rather than inferring its absence from the constraint of single-theme assignment alone.

The heatmap confirms that fragmentation is a substantive feature of the corpus rather than an artifact of the coding procedure. Critical Thinking (n = 50), Digital Literacy (n = 39), and STEM Education (n = 34) are each well represented individually. However, the strongest pairwise overlaps, CT×DL (n = 13), CT×STEM (n = 10), and DL×STEM (n = 10), still co-occur in fewer than 27% of the 101 articles. Overlap involving the constructs most central to the

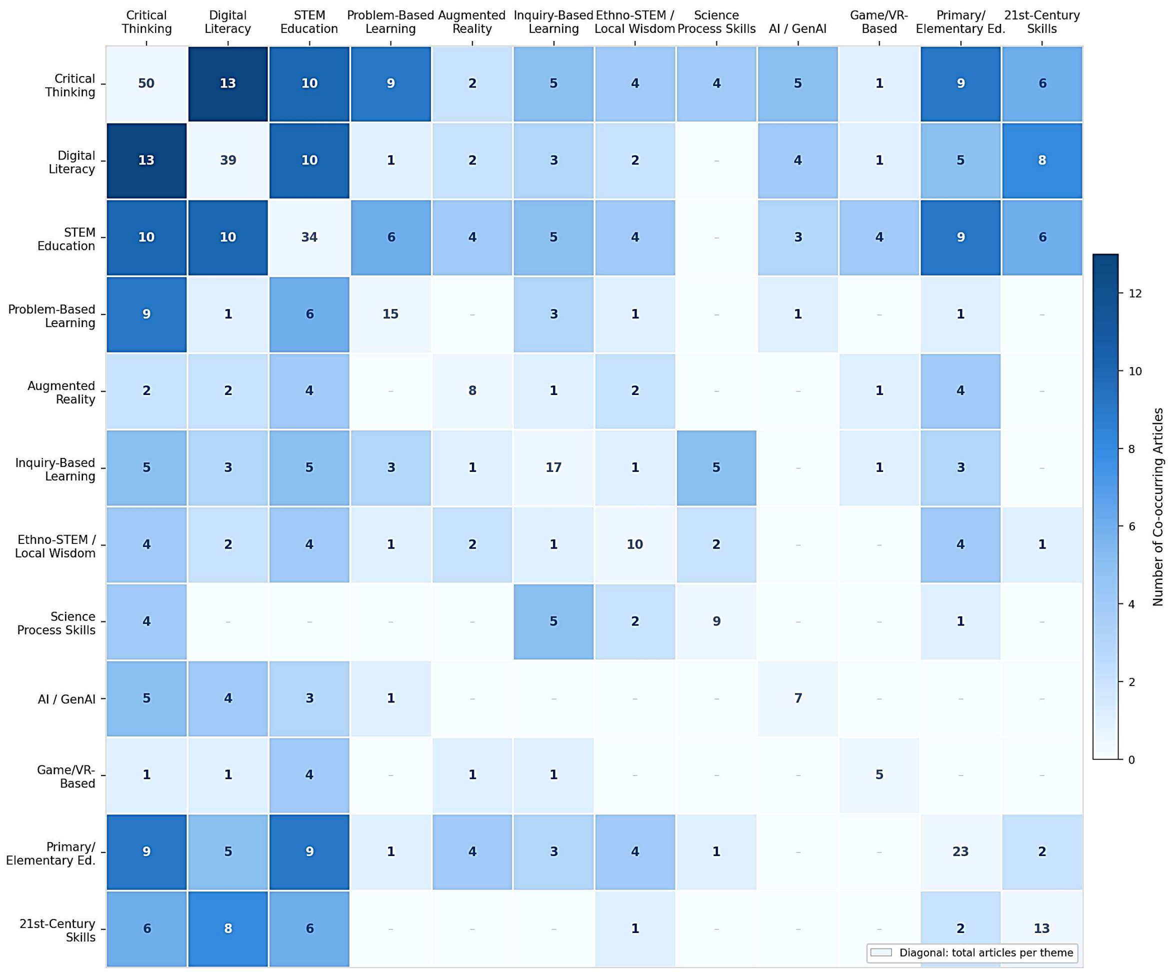

Figure 9. Article-Level co-occurrence heatmap of twelve thematic codes across 101 reviewed articles. diagonal cells (light blue) show the total number of articles assigned to each theme; off-diagonal cells show the number of articles in which two themes co-occur, with color intensity scaled to co-occurrence frequency

proposed integrative model is markedly sparser: Ethno-STEM co-occurs with Augmented Reality in only two articles and with Digital Literacy in three; the triple intersection of Ethno-STEM, Augmented Reality, and Digital Literacy is represented by a single study, and AI/GenAI never co-occurs with Ethno-STEM anywhere in the corpus. These article-level co-occurrence frequencies, rather than the single-dominant-theme tally alone, provide the direct empirical basis for concluding that a holistically integrated ethnoscience–digital inquiry–STEM model remains absent from the reviewed literature.

What Recommendations Support Future Research and Innovative Learning Model Development?

These identified research gaps directly underpin the urgency for developing a learning model that integrates these variables. The innovation of learning model is designed to: (a) integrate local wisdom as the contextual foundation of learning; (b) utilize digital technology (AR/VR) as a medium for exploration; (c) apply digital inquiry as the primary process of knowledge construction; (d) promote reflective knowledge for deepening understanding; and (e) develop digital literacy and critical thinking as integrated learning outcomes. Khurma and El Zein (2024), in their systematic review of inquiry skills teaching, found that science teachers in the UAE emphasize inquiry as the foundation of critical thinking, affirming that inquiry-based models hold strong pedagogical legitimacy globally.

■ CONCLUSION

This systematic literature review, employing the PRISMA method across 101 articles (2010–2026) from Scopus Q1–Q3 and SINTA S1–S2 journals, and reinforced by Dimensions AI data analysis (4,095 publications) and VOSviewer mapping (232 items, 5 clusters), yields several principal findings. The synthesis was conducted using Facione's critical thinking framework, providing a theoretically consistent basis for comparing heterogeneous empirical findings across the 101 reviewed studies. First, an ethnoscience approach integrated within PjBL-STEM has been demonstrated to effectively enhance students' critical and creative thinking skills, and scientific literacy, the two outcome variables actually measured in the reviewed studies. Second, AR and VR technologies provide immersive learning experiences that significantly improve conceptual understanding and motivation, with AR proving more feasible for large-scale implementation. Third, inquiry-based approaches, particularly those grounded in argumentation, reflection, and digital tools, constitute the most effective strategy for developing critical thinking skills, as confirmed by 26 of the 101 articles reviewed. Fourth, digital literacy is an essential competency that cannot be developed in isolation, but must be integrated within a holistic learning model. Dimensions AI trend data indicate a surge in publications in 2020 (1,053 articles) triggered by the pandemic, with a positive trend continuing through 2025, suggesting that the research momentum in this field is highly conducive. VOSviewer mapping identified 5 primary research clusters, in which the ethnoscience-digital inquiry integration cluster remains a relatively under-explored area compared to the teaching material development and science education research clusters.

The identified research gaps reveal the absence of an integrated model that systematically incorporates all four components simultaneously. This affirms the urgency of developing a new learning model, as an innovation addressing the needs of 21st-century science education in Indonesia. Future research is recommended to develop and empirically test the effectiveness of this new integrated learning model within the context of science learning at the junior and senior secondary school levels.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the preparation of this manuscript, the authors employed ChatGPT (OpenAI) and Claude (Anthropic) solely to assist with language refinement, sentence clarity and readability, and grammatical editing of selected sections of the manuscript. These tools were used under continuous human supervision and did not contribute to the intellectual content, scientific interpretation, research design, data analysis, or conclusions presented in this study. The bibliometric data collection, mapping, visualization, and analysis were conducted using Dimensions AI and VOSviewer as research and analytical tools, rather than generative AI systems for manuscript writing or content creation. All visualizations presented in this article were generated from the original research data using these analytical software packages and were carefully reviewed by the authors. The authors critically examined, verified, and revised all AI-assisted outputs and accept full responsibility for the accuracy, originality, integrity, and scientific content of the published manuscript.

REFERENCES

Abdurrahman, A., Setyaningsih, C. A., & Jalmo, T. (2019). Implementing Multiple Representation-Based Worksheet to Develop Critical Thinking Skills. *Journal of Turkish Science Education*, *16*(1), 138–155. https://doi.org/10.12973/tused.10271a

Adekunle, M., & Basil, C. (2026). AI-supported problem-based learning for enhancing computational thinking skills in STEM education. *Computers in Human Behavior: Artificial Humans*, *7*, 100263. https://doi.org/10.1016/j.chbah.2026.100263

Adhelacahya, K., Sukarmin, S., & Sarwanto, S. (2023). Impact of Problem-Based Learning Electronics Module Integrated with STEM on Students' Critical Thinking Skills. *Jurnal Penelitian Pendidikan IPA*, *9*(7), 4869–4878. https://doi.org/10.29303/jppipa.v9i7.3931

Afikah, A., Rohaeti, E., & Jumadi, J. (2024). Measuring Critical Thinking Skills in Science Learning: Students' Perception Versus Actual Performance. *TEM Journal*, *13*(4), 3266–3275. https://doi.org/10.18421/TEM134-61

Ainur, I., Raditya, F., Nurul, A., Dwi, A., Ramadani, R., & Habibbulloh, M. (2025). Ethnoscience-enhanced physics virtual simulation and augmented reality with inquiry learning: Impact on students ' creativity and motivation. *Thinking Skills and Creativity*, *57*, 101846. https://doi.org/10.1016/j.tsc.2025.101846

Akhdinirwanto, R. W., Agustini, R., & Jatmiko, B. (2020). Problem-Based Learning with Argumentation as A Hypothetical Model to Increase the Critical Thinking Skills for Junior High School Students. *Jurnal Pendidikan IPA Indonesia*, *9*(3), 340–350. https://doi.org/10.15294/jpii.v9i3.19282

Akmar, R., Sudarmin, Hafizan, E., & Sari, D. S. (2026). Ethnoscience in the Digital Age: A Systematic Review of Pedagogical Strategies for Scientific and Digital Literacy Development. *Jurnal Pendidikan MIPA*, *27*(1), 1411–2531. https://doi.org/10.23960/jpmipa

Amanah, P. D., Juddin, S., Maharani, G., & Gunawan, G. (2026). Decade Trends of Augmented Reality: Challenges and Opportunities in Elementary Science Learning 2017–2026. *Indonesian Journal of Elementary and Childhood Education*, *7*(1), 24–42. https://journal.publication-center.com/index.php/ijece/article/view/2006

Amanah, P. D., Martin, N., & Rokhmat, J. (2025). Research Trends on the Multiple Representation Learning Model, A Systematic Review (2016-2025). *Contextual Natural Science Education Journal (CNSEJ)*, *03*(1), 1–14. https://doi.org/10.29303/cnsej.v3i1.1070

Amanah, P. D., Rahayu, S., & Gunawan. (2025a). PBL-Based Science Modules Integrating Ethno-STEM and Augmented Reality/ : An Analysis of Practicality and Effectiveness. *Jurnal Pendidikan Fisika* *dan Teknologi (JPFT)*, *11*(2), 483–499. https://doi.org/10.29303/jpft.v11i2.10675

Amanah, P. D., Rahayu, S., Gunawan, & Doyan, A. (2025). Integrating PBL , Ethno-STEM , and AR for Critical Thinking and Digital Literacy/ : A Systematic Review (2016 – 2025). *Journal of Science and Science Education*, *6*(2), 183–195. https://doi.org/10.29303/jossed.v6i2.11431

Amanah, P. D., Rahayu, S., & Gunawan, G. (2025b). Validity and Reliability Analysis of Science Modules Using Problem-Based Learning Models Based on Ethno-STEM Assisted by Augmented Reality. *Kappa Journal*, *9*(2), 213–222. https://doi.org/10.29408/kpj.v9i2.31825

Amanah, P. D., Rahmatullah, R., & Gunawan, G. (2022). Augmented Reality in STEM Education: Trends and Insights From 2012 To 2021. *Indonesian Journal of STEM Education*, *4*(2), 103–117. https://journal.publication-center.com/index.php/ijse/article/view/1926

Amri, M. F., E.C.Prima, Winarno, N., & Mohamad, M. (2024). STEM Learning with A Simple Hydraulic Pump Project to Improve Student Communication and Collaboration Skills. *Jurnal Pendidikan IPA Indonesia*, *13*(3), 391–400. https://doi.org/10.15294/jpii.v13i3.5852

Arlinwibowo, J., Ishartono, N., Linguistika, Y., Purwoko, D., & Suprapto. (2023). Gamification in The STEM Domain Subject: The Prospective Method to Strengthen Teaching and Learning. *Jurnal Pendidikan IPA Indonesia*, *12*(4), 564–574. https://doi.org/10.15294/jpii.v12i4.48388

Atmojo, S. E., Anggriani, M. D., Rahmawati, R. D., Skotnicka, M., Wardana, A. K., & Anindya, A. P. (2025). Bridging Stem and Culture: the Role of Ethnoscience in Developing Critical Thinking and Cultural Literacy. *Jurnal Pendidikan IPA Indonesia*, *14*(2), 251–266. https://doi.org/10.15294/jpii.v14i2.23505

Bara, G., & Xhomara, N. (2020). The Effect of Student-Centered Teaching and Problem-Based Learning on Academic Achievement in Science. *Journal of Turkish Science Education*, *17*(2), 182–199. https://doi.org/10.36681/tused.2020.20

Batdý, V., Elaldý, Þ., Özçelik, C., Semerci, N., & Özkaya, Ö. M. (2024). Evaluation of the effectiveness of critical thinking training on critical thinking skills and academic achievement by using mixed-meta method. *Review of Education*, *12*(3), 1–32. https://doi.org/10.1002/rev3.70001

Behnamnia, N., Kamsin, A., Akmar, M., & Ismail, B. (2025). Relationship between creative thinking and outcomes in a digital STEM-based learning environment: A mixed methods case study. *Thinking Skills and Creativity*, *57*, 101816. https://doi.org/10.1016/j.tsc.2025.101816

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Choi, J. Y., Choi, S., Song, K., Baek, J., Kim, H., Choi, M., Kim, Y., Chu, S. H., & Shin, J. (2023). Everyday Digital Literacy Questionnaire for Older Adults: Instrument Development and Validation Study. *Journal of Medical Internet Research*, *25*, e51616. https://doi.org/10.2196/51616

Chusni, M. M. (2023). The implementation of Discovery-Based Multiple Represen tations Learning (DMRL) to enhance students' critical thinking skills. *Kasetsart Journal of Social Sciences*, *44*(2), 429–434. https://doi.org/10.34044/j.kjss.

2023.44.2.12

Citra, N. F., & Anggaryani, M. (2022). One Decade Trends of Virtual Reality Publication in Physics (2012-2021). *Jurnal Pendidikan MIPA*, *23*(4), 1583–1597. https://doi.org/10.23960/jpmipa/v23i4.pp1583-1597

Code, J., Forde, K., Moylan, R., Lutrin, A., Tasabehji, Z., Ralph, R., Mehta, A., Zap, N., & El, N. (2026). Expressions of learner agency in virtual inquiry: Linking agency and evidence-centered game design &. *Computers & Education*, *247*, 105590. https://doi.org/10.1016/j.compedu.2026.105590

Facione, P. A. (1990). Critical Thinking: A Statement of Expert Consensus for Purposes of Educational Assessment and Instruction. Research Findings and Recommendations (The Delphi Report). In *Newark, DE: American Philosophical Association*. https://eric.ed.gov/?id=ED315423&utm_source=chatgpt.com

Fang, G., Wang, J., Wing, P., Chan, K., & Kalogeropoulos, P. (2025). Understanding the gender divide in digital literacy in four European countries: A comprehensive decomposition analysis using unconditional quantile regression. *Computers & Education*, *229*, 105264. https://doi.org/10.1016/j.compedu.2025.105264

Farihah, M. J., Norawi, A. M., & Jahan, A. N. (2025). Game-Based STEM Module Development for KSSM Science Teachers. *Journal of Turkish Science Education*, *18*(2), 249–262. https://doi.org/10.36681/tused.2021.63

Guo, P., Saab, N., Post, L. S., & Admiraal, W. (2020). A review of project-based learning in higher education/ : Student outcomes and measures. *International Journal of Educational Research*, *102*, 101586. https://doi.org/10.1016/j.ijer.2020.101586

Gusli, T., Rusdinal, R., Jasrial, J., Tanucan, J. C. M., Harmanto, D., Rizal, M., Isa, M., & Yusra, A. (2025). Empowering Digital Literacy in Indonesian Islamic Education: A Meta-Analytic Exploration of Leadership's Role. *TEM Journal*, *14*(4), 3851–3864. https://doi.org/10.18421/TEM144-88

Han, S., Rosli, R., Capraro, M. M., & Capraro, R. M. (2016). The effect of Science, technology, engineering and mathematics (STEM) project based learning (PBL) on students' Achievement in four mathematics topics. *Journal of Turkish Science Education*, *13*(Special issue), 3–30. https://doi.org/10.12973/tused.10168a

Harlanu, M., Suryanto, A., Ramadhan, S., & Wuryandini, E. (2023). Construct validity of the instrument of digital skill literacy. *Cakrawala Pendidikan*, *42*(3), 781–790. https://doi.org/10.21831/cp.v42i3.59703

Hinostroza, J. E., Armstrong-gallegos, S., & Villafaena, M. (2024). Roles of digital technologies in the implementation of inquiry-based learning (IBL): A systematic literature review. *Social Sciences & Humanities Open*, *9*, 100874. https://doi.org/10.1016/j.ssaho.2024.100874

Hong, Q. N., Bartlett, G., Boardman, F., Cargo, M., Dagenais, P., Gagnon, M., Griffiths, F., Nicolau, B., Rousseau, M., Vedel, I., & Pluye, P. (2018). The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. *Canadian Intellectual Property Office*, *1*, 1–7. https://doi.org/10.3233/EFI-180221

Ibda, H., Syamsi, I., & Rukiyati. (2023). Digital literacy competency of elementary school teachers: A systematic literature review. *International Journal of Evaluation and Research in Education*, *12*(3), 1609–1617. https://doi.org/10.11591/ijere.

v12i3.24559

Ika, G., Winasis, S., Pratiwi, I., & Wildan, U. (2024). Strengthening digital literacy in Indonesia: Collaboration, innovation, and sustainability education. *Social Sciences & Humanities Open*, *10*, 101100. https://doi.org/10.1016/j.ssaho.2024.101100

Imjai, N., Aujirapongpan, S., & Yaacob, Z. (2024). Impact of logical thinking skills and digital literacy on Thailand's Generation Z accounting students ' internship effectiveness: Role of self-learning capability. *International Journal of Educational Research Open*, *6*, 100329. https://doi.org/10.1016/j.ijedro.2024.100329

Jegstad, K. M., Heggernes, S. L., Evy, J., Ryen, E., Svanes, I. K., & Hilde, T. (2025). Approaches to critical thinking in primary education classrooms: A systematic review. *Educational Research Review*, *48*, 100711. https://doi.org/10.1016/j.edurev.2025.100711

Jiang, L., & Gu, M. M. (2025). Enabling critical digital literacies through GenAI-assisted multimodal composing: A longitudinal inquiry of an ethnic minority English teacher. *System*, *135*, 103870. https://doi.org/10.1016/j.system.2025.103870

Jufrida, Kurniawan, W., & Basuki, F. R. (2024). Ethnoscience Learning: How Do Teacher Implementing to Increase Scientific Literacy in Junior High School. *International Journal of Evaluation and Research in Education*, *13*(3), 1719–1730. https://doi.org/10.11591/ijere.v13i3.26180

Juniawan, E. R., Sumarni, W., & Prasetya, A. T. (2024). Development of Ethno-STEM-Loaded Digital Science Teaching Materials the Process of Making Traditional Sidoarjo Snacks Material of Force and Object Motion to Train Science Literacy in Elementary School Students. *Jurnal Penelitian Pendidikan IPA*, *10*(1), 325–337. https://doi.org/10.29303/jppipa.v10i1.5948

Kaçar, S., & Balim, A. G. (2021). Investigating the Effects of Argument-Driven Inquiry Method in Science Course on Secondary School Students' Levels of Conceptual. *Journal of Turkish Science Education*, *18*(4), 816–845. https://doi.org/10.36681/tused.2021.105

Khurma, O. A., & El Zein, F. (2024). Inquiry Skills Teaching and its Relationship with UAE Secondary School Students' Critical Thinking: Systematic Review of Science Teachers' Perspectives. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(2), em2397. https://doi.org/10.29333/ejmste/14155

Loyens, S. M. M., Meerten, J. E. van, Schaap, L., & Wijnia, L. (2023). Situating Higher Order , Critical , and Critical Analytic Thinking in Problem and Project Based Learning Environments/ : A Systematic Review. In *Educational Psychology Review* (Issue 35). Springer US. https://doi.org/10.1007/s10648-023-09757-x

Luo, L., Shen, W., Ye, Q., Zhan, Z., & Lin, W. (2025). Effect of virtual simulation supported museum based learning on primary school students' multidisciplinary knowledge acquisition, learning motivation, critical thinking, creativity, and problem solving skills in C STEAM courses. *Future in Educational Research*, *3*(2), 259–281. https://doi.org/10.1002/fer3.70006

Maisarah, S., Miriam, S., Mahtari, S., & Suyidno, S. (2022). Autonomy-Based STEM Learning An Innovative Solution to Improve Students' Digital Literacy. *Jurnal Pendidikan MIPA*, *23*(2), 1069–1081. https://doi.org/10.23960/jpmipa/

v23i3.pp1069-1081

Muhfahroyin, M., Rachmadiarti, F., Mahanal, S., Zubaidah, S., & Siagiyanto, B. E. (2023). Improving critical thinking of low ability students through TPS and PBL integration in biology learning. *Journal of Turkish Science Education*, *20*(4), 606–618. https://doi.org/10.36681/tused.2023.034

Mui, Y., Heung, E., Yin, H., English, L., & Chiu, T. K. F. (2026). Theorizing AI literacy development using Habermas ' three cognitive knowledge interests from a systematic review: A STEM interdisciplinary perspective. *Computers & Education Journal*, *242*, 105492. https://doi.org/10.1016/j.compedu.2025.105492

Muktiani, N. R., Soegiyanto, Siswantoyo, Rahayu, S., & Hermawan, H. A. (2022). Augmented reality mobile app-based multimedia learning of Pencak Silat to enhance the junior high school students' learning outcomes. *Cakrawala Pendidikan*, *41*(2), 553–568. https://doi.org/10.21831/cp.v41i2.49217

Ng, D. T. K., Yee, W., Lai, W., Jong, M. S., & Wui, C. (2024). Using cospaces in augmented reality digital story creation: A thematic analysis. *Computers & Education: X Reality*, *5*, 100090. https://doi.org/10.1016/j.cexr.2024.100090

Oscar, B., & Ana, V. (2026). Pedagogical mediation with ICT for the development of critical thinking in primary education: A systematic review. *Thinking Skills and Creativity*, *60*, 102085. https://doi.org/10.1016/j.tsc.2025.102085

Özelçi, S. Y., & Çalýþkan, G. (2019). What is critical thinking? A longitudinal study with teacher candidates. *International Journal of Evaluation and Research in Education*, *8*(3), 495–509. https://doi.org/10.11591/ijere.v8i3.20254

Pamorti, O. A., Winarno, & Suryandari, K. C. (2024). Effectiveness of Augmented Reality Based Learning Media to Improve Critical Thinking Skills on IPAS Material. *Jurnal Penelitian Pendidikan IPA*, *10*(5), 2211–2219. https://doi.org/10.29303/jppipa.v10i5.7139

Perdana, R., Jumadi, J., Rosana, D., & Riwayani, R. (2020). The online laboratory simulation with concept mapping and problem based learning (Ols-cmpbl): Is it effective in improving students' digital literacy skills? *Cakrawala Pendidikan*, *39*(2), 382–394. https://doi.org/10.21831/cp.v39i2.31491

Prahani, B. K., Saphira, H. V., Wýbowo, F. C., Musbah, & Sulaeman, N. F. (2022). Trend and Visualization of Virtual Reality & Augmented Reality in Physics Learning From 2002-2021. *Journal of Turkish Science Education*, *19*(4), 1096–1118. https://doi.org/10.36681/tused.2022.164

Prananta, A. W., Rohman, A., Agustin, R., & Pranoto, N. W. (2024). Augmented Reality for Interactive, Innovative and Fun Science Learning: Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *10*(Special Issue), 45–51. https://doi.org/10.29303/jppipa.v10ispecialissue.7519

Premthaisong, S., & Srisawasdi, N. (2024). An effect of technology-infused active inquiry learning in primary school science on students' conceptions of learning science. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(6), em2463. https://doi.org/10.29333/EJMSTE/14662

Puger, I. G. N., Deng, J. B., Antara, I. G. W. S., Dewantara, K. A. K., Sugiarta, M., Veliz, L., Sudatha, I. G. W., & Sudarma, I. K. (2024). Metacognition-Based Learning Model: Improving Agile Innovation And

Critical Thinking Skills Of Students In Science Learning In Elementary Schools. *Jurnal Pendidikan IPA Indonesia*, *3*(2), 128–133. https://doi.org/10.15294/jpii.v13i2.1375

Qumillaila, Q., Susanti, B. H., & Zulfiani, Z. (2017). Pengembangan Augmented Reality Versi Android Sebagai Media Pembelajaran Sistem Ekskresi Manusia. *Jurnal Cakrawala Pendidikan*, *36*(1), 57–69. https://doi.org/10.21831/cp.v36i1.9786

Rahmat, A. D., Kuswanto, H., Wilujeng, I., & Pratidhina, E. (2023). Improve critical thinking skills using traditional musical instruments in science learning. *International Journal of Evaluation and Research in Education*, *12*(4), 2165–2175. https://doi.org/10.11591/ijere.v12i4.25753

Ramlawati, Sari, N. I., Kusumawati, R., Yesin, M., Ilmi, N., & Arsyad, A. A. (2025). The Effect of Differentiated Science Inquiry Learning Model Based on Teaching at the Right Level on Students' Critical Thinking and Science Process Skills. *Jurnal Pendidikan IPA Indonesia*, *14*(1), 1–16. https://doi.org/10.15294/jpii.v14i1.19479

Rijal, M., Mastuti, A. G., Safitri, D., Bachtiar, S., & Samputri, S. (2021). Differences in learners' critical thinking by ability level in conventional, NHT, PBL, and integrated NHT-PBL classrooms. *International Journal of Evaluation and Research in Education*, *10*(4), 1133–1139. https://doi.org/10.11591/IJERE.V10I4.21408

Ririen, D., & Heriasman, H. (2021). Does Self-Management Affect Students' Digital Literacy? Evidence from a Campus in Riau Province. *Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran Dan Pembelajaran*, *7*(4), 946. https://doi.org/10.33394/jk.v7i4.4333

Rokhmat, J., Gunawan, G., Sukarso, A., Rahmatiah, R., Mahmudah, H., & Amanah, P. D. (2025). Revealing the Weaknesses of Applying Gamification in Science Learning and Overcoming It: A Systematic Review. *TEM Journal*, *14*(3), 2462–2471. https://doi.org/10.18421/tem143-50

Rosyidah, F., Susantini, E., Yuliani, Y., & Nisa', K. (2025). Local Wisdom and STEM in Science Education to Support SDG-4: A Systematic Review. *Jurnal Pendidikan IPA Indonesia*, *14*(4), 654–666. https://doi.org/10.15294/jpii.v14i4.34450

Rusydiyah, E. F., Purwati, E., & Prabowo, A. (2020). How to use digital literacy as a learning resource for teacher candidates in Indonesia. *Cakrawala Pendidikan*, *39*(2), 305–318. https://doi.org/10.21831/cp.v39i2.30551

Shahab, C., & Barak, M. (2026). Critical thinking in higher education: Identifying the pedagogical practices and modes of engagement. *Thinking Skills and Creativity*, *59*, 102041. https://doi.org/10.1016/j.tsc.2025.102041

Shylvia, P. C., Yulia, C., Sudiapermana, E., & Sujana, A. (2025). Problem-Based Learning in the Context of Mathematical Critical Thinking A Bibliometric Trend Analysis. *Jurnal Pendidikan MIPA*, *26*(2), 1219–1233. https://doi.org/10.23960/jpmipa/v26i2.pp1219-1233

Sogalrey, F. A. M., Safitri, F., & Tijow, M. A. (2024). Digital Literacy Research in Education: Trends and Insights. *Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran Dan Pembelajaran*, *10*(3), 1169–1180. https://doi.org/10.33394/jk.v10i3.12490

Stefany, S., & Helmi, J. (2024). Digital literacy and online course design: Study of Indonesian educators. *Cakrawala Pendidikan*, *43*(3), 723–736. https://doi.org/10.21831/cp.v43i3.71403

Strauss, A., & Corbin, J. (1998). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory (2nd ed.)*. Sage Publications.

Suciati, R., Susilo, H., Lestari, U., & Gofur, A. (2022). Critical thinking skills: Profile and mastering concepts of undergraduate students. *International Journal of Evaluation and Research in Education*, *11*(3), 1250–1257. https://doi.org/10.11591/ijere.v11i3.22409

Sumarni, W., & Kadarwati, S. (2020). Ethno-stem project-based learning: Its impact to critical and creative thinking skills. *Jurnal Pendidikan IPA Indonesia*, *9*(1), 11–21. https://doi.org/10.15294/jpii.v9i1.21754

Sundgren, M., Jaldemark, J., & Cleveland-innes, M. (2023). Disciplinary differences and emotional presence in communities of inquiry: Teachers' expressions of digital technology-enabled teaching. *Computers and Education Open*, *4*, 100134. https://doi.org/10.1016/j.caeo.2023.100134

Suningsih, A., Budayasa, I. K., & Ismail, I. (2025). Leveling of Critical Thinking Abilities of Junior High School Students in Solving Geometry Problems. *TEM Journal*, *14*(1), 481–491. https://doi.org/10.18421/TEM141-43

Susanta, A., Susanto, E., Rusnilawati, Sumardi, H., & Ali, S. R. B. (2025). Literacy skills through the use of digital STEAM-inquiry learning modules: A comparative study of urban and rural elementary schools in Indonesia. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(4), em2615. https://doi.org/10.29333/ejmste/16170

Suwandi, S. Y. P. A., Sukarmin, Cahyaningrum, S. E., Satriawan, M., & Soraya, F. (2025). Ethnoscience Approach to Improve Science Literacy on Chemical Bonding: A Thematic Synthesis. *Jurnal Pendidikan MIPA*, *26*(3), 1909–1931. https://doi.org/10.23960/jpmipa.v26i3.pp1909-1931

Szalay, L., Tóth, Z., Borbás, R., & Füzesi, I. (2025). Effect of Guided Inquiry on Junior High School l Earners' Experimental Design Skills in Solving Chemistry Problems. *Journal of Turkish Science Education*, *22*(3), 584–611. https://doi.org/10.36681/tused.2025.030

Tabakova-Komsalova, V., Stoyanov, I., Cholakov, G., & Maglizhanova, M. (2024). Introducing Artificial Intelligence to Secondary Schools Through STEM Learning and the Logic Programming Language Prolog. *TEM Journal*, *13*(4), 3221–3230. https://doi.org/10.18421/TEM134-56

Tafakur, Retnawati, H., & Shukri, A. A. M. (2023). Effectiveness of project-based learning for enhancing students critical thinking skills: A meta-analysis. *JINoP (Jurnal Inovasi Pembelajaran)*, *9*(2), 191–209. https://doi.org/10.22219/jinop.v9i2.22142

Thanh, T. N. T., Nguyen, T. T. H., Le, T. H. C., Ha, T. H. D., Thanh, V. N. T., & Thanh, P. H. (2025). Science mapping research of STEM in primary schools: A bibliometric analysis from Scopus database (2004-2024). *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(6), em2650. https://doi.org/10.29333/ejmste/16510

Tohri, A., Rasyad, A., Sururuddin, M., & Istiqlal, L. M. (2022). The urgency of Sasak local wisdom-based character education for elementary school in East Lombok, Indonesia. *International Journal of*

Evaluation and Research in Education, *11*(1), 333–344. https://doi.org/10.11591/ijere.v11i1.21869

Tuyet, T. L. T., Thi, K. N., Duc, H. T., Giao, X. T. T., Thi, N. V., Tuong, V. H. K., Nhu, U. D. T., & Mai, A. L. T. (2024). STEM education in primary schools of Southeast Asian countries: An analysis of scientific publications in the Scopus database from 2000 to 2022. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(4), em2433. https://doi.org/10.29333/ejmste/14432

Usman, G. B. T., Ali, M. N., & Ahmad, M. Z. (2023). Effectiveness of STEM Problem-Based Learning on the Achievement of Biology among Secondary School Students in Nigeria. *Journal of Turkish Science Education*, *20*(3), 453–467. https://doi.org/10.36681/tused.2023.026

Utami, K., Apriliya, S., & Saputra, E. (2022). The Urgency of Digital Literacy and Ethics for Parents in Educating Children in the Digital Age. *Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran Dan Pembelajaran*, *8*(1), 58. https://doi.org/10.33394/jk.v8i1.4605

Verawati, N. N., Putu, S., Rokhmat, J., Harjono, A., Makhrus, M., & Sukarso, A. S. (2025). *Integrating Ethnoscience-PBL and Virtual Technology to Improve Critical Thinking Skills/ : A Literature Review and Model Design*. *14*(2), 1878–1894. https://doi.org/10.18421/TEM142

Wang, S., & Xu, F. (2026). From scroll to screen: Cultivating critical digital literacy through algorithm-aware writing pedagogies in EAP. *Journal of English for Academic Purposes*, *81*, 101676. https://doi.org/10.1016/j.jeap.2026.101676

Wei, X., Wang, L., Koszalka, T. A., Lee, L., & Liu, R. (2025). Enhancing pre-service teachers ' reflective thinking skills through generative AI-assisted digital storytelling creation: A three-dimensional framework analysis. *Computers & Education*, *235*, 105356. https://doi.org/10.1016/j.compedu.2025.105356

Wibawa, I. M. C., Rati, N. W., Werang, B. R., & Deng, J. B. (2024). Increasing Science Learning Motivation in Elementary Schools: Innovation With Interactive Learning Videos Based on Problem Based Learning. *Jurnal Pendidikan IPA Indonesia*, *13*(3), 504–513. https://doi.org/10.15294/jpii.v13i3.6049

Widiyatmoko, A., Nugrahani, R., Yanitama, A., & Darmawan, M. S. (2023). The Effect of Virtual Reality Game-Based Learning to Enhance STEM Literacy in Energy Concepts. *Jurnal Pendidikan IPA Indonesia*, *12*(4), 648–657. https://doi.org/10.15294/jpii.v12i4.48265

Winarto, Sarwi, S., Cahyono, E., & Sumarni, W. (2022). Developing a Problem-Solving Essay Test Instrument (PSETI) in the Instruction of Basic Science Concepts in Ethnoscience Context. *Journal of Turkish Science Education*, *19*(1), 37–51. https:/ /doi.org/10.36681/tused.2022.108

Yang, W., Liang, L., Xiang, S., & Yeter, I. H. (2025). Making a Makerspace in early childhood education: Effects on children's STEM thinking skills and emotional development. *Thinking Skills and Creativity*, *56*, 101754. https://doi.org/10.1016/j.tsc.2025.101754