



## Integrating STEM Approaches into Interactive Digital Modules for Supporting Higher-Order Thinking Skills in Science Education: A Systematic Literature Review

<sup>1</sup>\*Rahmawati, <sup>2</sup>Tri Hastiti Fiskawarni, <sup>3</sup>Andi Arie Andriani, <sup>4</sup>Widiasih

<sup>1</sup> Magister Pendidikan Dasar, Universitas Muhammadiyah Makassar, Makassar, Indonesia

<sup>2,3</sup> Program Studi Pendidikan Fisika, Universitas Muhammadiyah Makassar, Makassar, Indonesia

<sup>4</sup> Program Studi Pendidikan Fisika, Universitas Terbuka, Tangerang Selatan, Indonesia

\*Corresponding Author e-mail: [rahmawatisyam@unismuh.ac.id](mailto:rahmawatisyam@unismuh.ac.id)

Received: April 2026; Revised: May 2026; Published: July 2026

### Abstract

The integration of Science, Technology, Engineering, and Mathematics (STEM) approaches into interactive digital modules (IDMs) has gained prominence as a strategy for supporting Higher-Order Thinking Skills (HOTS) in science education. This PRISMA-based systematic literature review synthesizes empirical studies published between 2022 and 2026 to examine how STEM-embedded digital modules are designed, implemented, and evaluated in relation to HOTS outcomes. Using PRISMA procedures and structured Boolean searches across major databases, 22 studies were selected and analyzed across four themes: STEM integration models, interactive design mechanisms, empirical effectiveness, and implementation challenges including scalability and equity. The findings show that modules grounded in the Engineering Design Process (EDP), inquiry-based learning, and adaptive feedback were most frequently associated with short-term improvements in analytical reasoning, problem-solving, and evaluative thinking. Quantitative evidence indicates that one AI-assisted module reported an 18.4% improvement in applied reasoning; however, differences in instruments and study designs limit direct comparison across HOTS measures. Some studies also reported short-term retention effects. The review proposes an integrative framework linking depth of STEM integration, interactive mechanisms, contextual moderators, and HOTS outcomes, and highlights inclusive design, continuous feedback, collaboration, and teacher training as key principles for sustainable, equitable, and evidence-informed implementation.

**Keywords:** STEM approach; Interactive digital modules; Higher-order thinking skills; Science education; Systematic literature review

**How to Cite:** Rahmawati, R., Fiskawarni, T. H., Andriani, A. A., & Widiasih, W. (2026). Integrating STEM Approaches into Interactive Digital Modules for Supporting Higher-Order Thinking Skills in Science Education: A Systematic Literature Review. *Prisma Sains: Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, 14(3), 1214–1239. <https://doi.org/10.33394/j-ps.v14i3.20415>



<https://doi.org/10.33394/j-ps.v14i3.20415>

Copyright © 2026, Rahmawati et al.

This is an open-access article under the [CC-BY](https://creativecommons.org/licenses/by/4.0/) License



## INTRODUCTION

The transition to digital transformation in education has substantially influenced the design, implementation, and evaluation of interactive digital modules in science education. In response to the increasing technological integration in educational practices, this shift is intended to enhance engagement and improve learning outcomes. Interactive modules are now an integral part of STEM education, with the increased use of digital tools to facilitate adaptive, student-centered learning.

High-speed internet, mobile technology, and educational software have made possible the creation of interactive digital modules containing multimedia, simulations, and gamification. In this review, an interactive digital module (IDM) is defined as a structured digital learning unit that combines instructional content with at least one bidirectional

interactive feature, such as embedded assessment, simulation, adaptive feedback, learner control, reflective prompts, or collaborative digital workspaces. Evidence suggests that these tools increase accessibility of scientific content, while also promoting experiential learning through active participation in simulations and practical problem-solving (Uzunova-Dimitrova & Zhelezov, 2024).

Moreover, the use of digital modules facilitates differentiated instruction by adjusting student learning pace and style to suit different academic needs. Several studies have shown that these modules can improve STEM academic motivation and achievement (Asrizal et al., 2022). Integrated collaboration features of IDMs enable teamwork, peer-learning, and skills related to scientific professions (Santos et al., 2023).

The inclusion of STEM approaches in educational materials is based on constructivist theory, which advocates for the use of hands-on learning and problem-solving techniques. In this study, integrated STEM refers not merely to the presence of science, technology, engineering, and mathematics labels, but to the purposeful connection of two or more STEM domains through authentic problems, inquiry processes, design tasks, or Engineering Design Process cycles. Through the integration of STEM fields, students are equipped with the necessary skills in analysis, creativity, and collaboration for technologically advanced workplaces (Guo et al., 2025). Systematic reviews confirm that integrated STEM learning improves engagement, motivation, and HOTS development (Nor & Halim, 2023; Sutarto et al., 2023).

Besides memory and understanding, HOTS involves higher cognitive processes such as analysis, evaluation, creation, synthesis, application, and complex problem-solving. Science education has increasingly focused on developing critical thinking and problem-solving skills as core learning outcomes (Li, 2025). Despite the need for modern-day research emphasizing collaboration and interdisciplinary thinking, Bloom's taxonomy remains a primary method for categorizing HOTS (Nasution, 2025). HOTS development has been associated with inquiry-based, project-based, and problem-based approaches to learning (Manolov, 2025).

The implementation of HOTS involves tasks such as conducting experiments, interpreting data, developing hypotheses, and engaging in peer discussions (Manolov, 2025; Syahfutra et al., 2024). By utilizing simulations and reflective feedback, these performance-based assessments can be embedded within digital modules (Bukhari et al., 2025). Accordingly, this review treats metacognition and self-regulation as supporting mechanisms for HOTS unless the original studies explicitly measured them as higher-order cognitive outcomes.

Studies repeatedly establish a connection between digital modules and improved HOTS outcomes. Augmented reality (AR), simulations, and inquiry-driven content can support students in synthesizing knowledge and applying it to new contexts (Manolov, 2025). Practicum simulation fosters the development of analytical abilities by connecting theoretical concepts with applied scientific practice.

Enhanced motivation and critical evaluation are achieved through the use of interactive platforms that offer real-time feedback and support problem-based learning (Bukhari et al., 2025; Rajput & Chaudhary, 2025). In addition, real-time feedback mechanisms can promote metacognitive reflection by helping learners monitor misconceptions, revise strategies, and evaluate their reasoning processes (Manolov, 2025).

While digital modules are increasingly used in science education, many remain limited in terms of meaningful interdisciplinary STEM integration. Studies indicate a dearth of coherent frameworks for unifying STEM disciplines within modules, leading to fragmented learning (Yang & Chen, 2024; S. Zhou & Bakhir, 2024). This limitation is particularly important because STEM integration can vary in depth, ranging from multidisciplinary arrangements in which disciplines are placed side by side, to interdisciplinary and

transdisciplinary designs in which learners solve authentic problems across disciplinary boundaries.

Additionally, many educators have limited preparation for integrating digital media into STEM-oriented pedagogy. Integrated STEM learning's potential is diminished by the absence of targeted professional development in IDMs (Zhou & Bakhir, 2024). Technical limitations and disparities in digital infrastructure also limit module effectiveness in under-resourced settings (Nor & Halim, 2023; Okwara & Pretorius, 2023). These challenges are compounded when module content is poorly aligned with curriculum standards, thereby reducing instructional coherence and classroom applicability (Nungu et al., 2023).

The focus on interactive modules is distinct from passive e-learning platforms because they emphasize engagement, contextual learning, and immediate feedback. Simulations, problem-solving, and collaborative features engage students' higher-order cognitive processes (Clark et al., 2024; Huang et al., 2025; Sutarto et al., 2023; Xu & Zhou, 2022). However, the mere presence of interactive features does not guarantee HOTS development unless those features are aligned with explicit cognitive goals, scaffolding strategies, and valid assessment of higher-order outcomes.

The integration of experiential learning in IDMs facilitates the application of scientific knowledge to real-life challenges, promoting critical thinking and creativity (Hu et al., 2024). Guo et al. (2025) recommend self-regulation and reflection through feedback mechanisms, while Xu & Zhou (2022) demonstrate how collaborative tools can enhance soft skill development by mimicking scientific team environments. Nevertheless, prior studies and reviews have not sufficiently clarified how the depth of STEM integration, interactive design mechanisms, and implementation conditions jointly shape HOTS outcomes in science education. Therefore, the novelty of this review lies in mapping STEM integration depth to IDM design features, HOTS-related outcomes, and contextual barriers through an integrative synthesis framework.

To address this gap, this review is guided by four research questions:

- 1) What models of STEM integration are embedded in interactive digital modules in science education?
- 2) Which interactive design features are associated with HOTS development?
- 3) What empirical evidence supports the effectiveness of STEM-integrated IDMs for HOTS, including retention and transfer?
- 4) What implementation challenges affect scalability, equity, and classroom adoption?

## METHOD

### Research Type

A systematic literature search was conducted using Scopus as one primary academic databases. This database was selected for its comprehensive indexing of peer-reviewed educational technology and STEM education research. The review followed PRISMA procedures to ensure transparent identification, screening, eligibility assessment, and inclusion of studies. To improve replicability, the search strategy was organized around three core constructs: interactive digital modules, integrated STEM, and higher-order thinking skills. Boolean operators (AND, OR, NOT) were utilized to construct search strings that combined core concepts such as “interactive digital module,” “STEM integration,” and “higher-order thinking skills.” The main search string was: ("STEM" OR "integrated STEM" OR "Science Technology Engineering Mathematics" OR "engineering design process") AND ("interactive digital module" OR "digital module" OR "e-module" OR "interactive e-module" OR "interactive learning module" OR "multimedia module" OR "simulation-based module" OR "virtual laboratory" OR "interactive digital learning") AND ("higher-order thinking" OR "HOTS" OR "critical thinking" OR "analytical thinking" OR "scientific reasoning" OR "problem solving" OR "problem-solving" OR "evaluative thinking") AND ("science

education" OR "science learning" OR physics OR chemistry OR biology OR "STEM education").

Additional keyword refinement included combinations such as “STEM AND digital learning,” “engineering design process AND digital module,” “interactive e-module AND HOTS,” and “problem-based learning AND scientific reasoning” to improve specificity (Chen et al., 2025; Hermita et al., 2023; Asilevi et al., 2025). To further enhance the accuracy of search results, terms such as "diagnostic assessments," "conceptual understanding," and "misconceptions" were used to target empirical research in science education (Hartelt & Martens, 2025; Korur, 2025; Çelikkanlı & Tan, 2022). Backward and forward snowballing was also employed to identify additional studies. Search documentation included the database searched, exact query string, applied filters, search date, number of records retrieved from each database, duplicate-removal decisions, and metadata export for PRISMA documentation. The publication window was standardized to 2022–2026 to align the search period, eligibility criteria, abstract, and final synthesis corpus.

#### *Inclusion Criteria:*

1. Peer-reviewed journal articles or high-quality peer-reviewed conference proceedings in educational technology, STEM education, or science education;
2. Empirical or design-based studies examining STEM integration within interactive digital modules;
3. Studies focusing on science education (K–12 or higher education);
4. Explicit outcomes related to HOTS (e.g., critical thinking, scientific reasoning, analytical problem-solving);
5. Publications from 2022 to 2026 in English; and
6. Studies that reported sufficient methodological information on participants, intervention design, learning context, and HOTS-related outcomes.

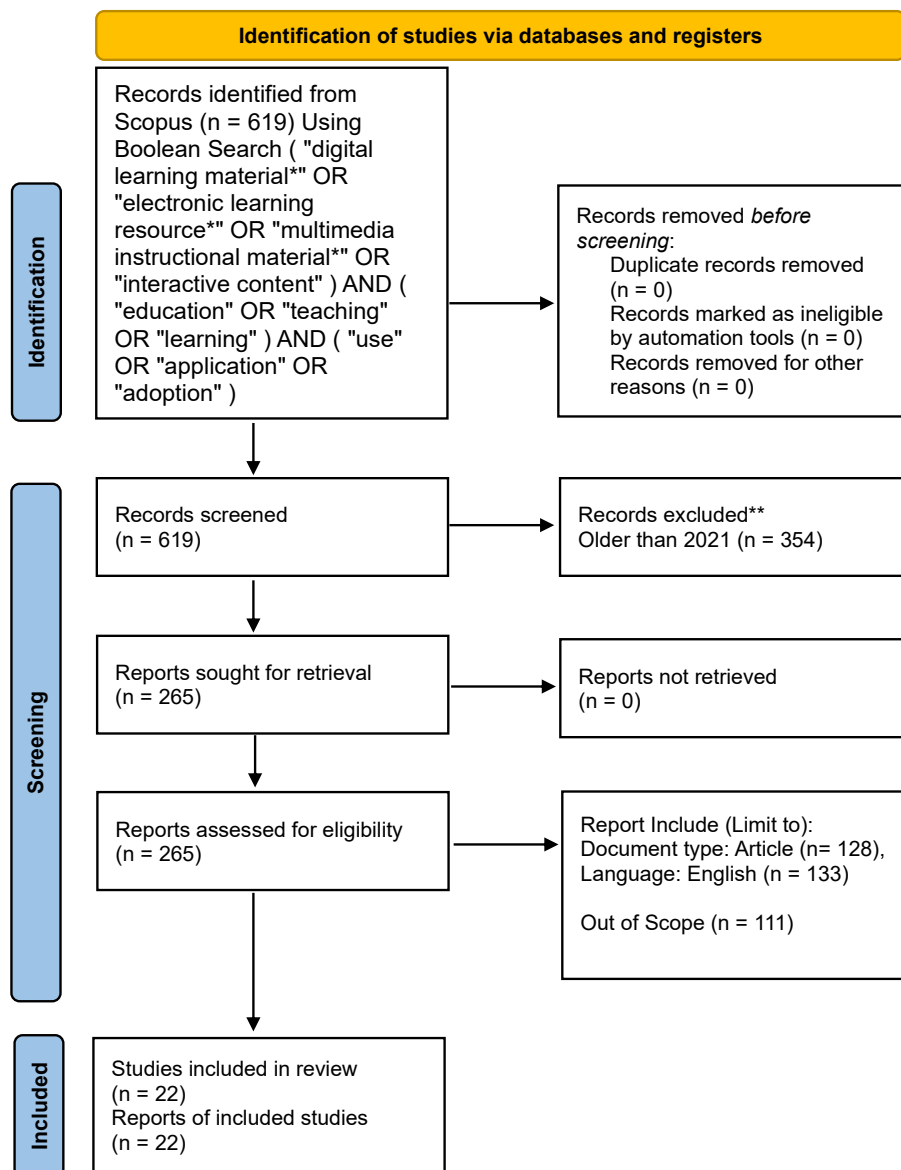
#### *Exclusion Criteria:*

1. Studies without digital learning modules or STEM-based interventions;
2. Theoretical or descriptive papers without empirical findings;
3. Non-English publications or articles outside the science learning context (Stanja et al., 2022; Jančaříková & Jančařík, 2022);
4. Studies using passive e-learning materials without bidirectional interactivity, embedded assessment, simulation, adaptive feedback, reflective prompts, or collaborative digital features;
5. Studies that used the term STEM only as a label without evidence of integration across two or more STEM domains, design processes, inquiry activities, or authentic problem-solving tasks; and
6. Studies that reported general achievement only and did not provide HOTS-related indicators, such as analysis, evaluation, creation, scientific reasoning, problem-solving, or conceptual transfer.

These criteria were informed by best practices in systematic STEM reviews and were designed to isolate studies demonstrating the impact of interactive STEM-IDMs on student cognitive outcomes (Steinwachs & Martens, 2025; Putri et al., 2022; Paçacı et al., 2023). For this review, an interactive digital module was defined as a structured digital learning unit containing instructional content and at least one bidirectional interactive feature. Integrated STEM was coded only when the study connected two or more STEM domains through inquiry, design tasks, problem-based learning, or Engineering Design Process activities. HOTS outcomes were limited to higher cognitive processes, including analysis, evaluation, creation, scientific reasoning, problem-solving, and transfer; metacognition and self-regulation were treated as supporting mechanisms unless the original study explicitly measured them as HOTS-related outcomes.

The screening process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A total of 619 records were identified using the Boolean search strategy across databases. After removing duplicates, title and abstract screening were conducted, excluding 354 studies published before 2021. Full-text screening was applied to 265 eligible studies, resulting in 22 final studies included in the review.

A two-reviewer protocol was followed to ensure reliability. Disagreements were resolved through consensus or third-party adjudication. The PRISMA flow diagram (Figure 1) illustrates the screening and selection process in detail.



**Figure 1.** PRISMA Flow Diagram

To assess methodological quality, this review applied the Mixed Methods Appraisal Tool (MMAT) and the Critical Appraisal Skills Programme (CASP). MMAT was used to evaluate studies using qualitative, quantitative, or mixed methods, ensuring consistency across diverse research designs (Guerra-Reyes et al., 2024; Nasir et al., 2024; Anastácio et al., 2022). CASP provided structured checklists adapted for educational technology contexts (Çelikkanlı & Kızılcık, 2022). Each study was appraised for clarity of research questions, appropriateness of design, sampling adequacy, validity of outcome measures, transparency of analysis, and relevance to STEM-IDM and HOTS outcomes. Appraisal results were summarized in a quality appraisal table and used to qualify the strength of evidence rather than to automatically exclude

studies. Studies with weaker methodological reporting were retained only for contextual or descriptive synthesis and were not used as primary evidence for strong effectiveness claims.

Data were extracted using a standardized schema, which included study context, educational level, STEM integration model, module characteristics, interactivity features, HOTS outcomes, and limitations. The extraction template also recorded country, sample size, research design, intervention duration, assessment instrument, validation status of HOTS measures, retention or transfer testing, reported effect direction, and implementation constraints. STEM integration depth was coded as multidisciplinary, interdisciplinary, or transdisciplinary based on the degree of conceptual connection across STEM domains and the presence of authentic problem-solving or design-based tasks. IDM features were coded according to the presence of simulations, adaptive feedback, embedded assessment, learner control, reflective prompts, collaborative functions, and multimodal representations. These data informed the construction of synthesis tables for each of the four themes. A hybrid synthesis approach was adopted:

1. Narrative synthesis was used to summarize outcomes across diverse study types.
2. Thematic synthesis helped identify recurring patterns in interactive design and HOTS development.
3. Effect-direction synthesis provided insight into the directionality of impacts, whether positive, neutral, or negative (Paçacı et al., 2023; Begum et al., 2023; Voronkin & Lushchin, 2025; Li et al., 2024).

Because the included studies varied substantially in educational level, intervention format, duration, research design, and HOTS measurement instruments, statistical meta-analysis was not conducted. Instead, evidence was synthesized by research question and graded descriptively according to study design, methodological quality, validity of HOTS measurement, and whether outcomes were immediate, retained, or transferred. This combined strategy improved transparency and enabled cautious cross-study comparison in the synthesis of heterogeneous STEM education research. Claims of effectiveness were therefore interpreted in relation to evidence strength, with stronger claims reserved for studies using clearer intervention designs, validated or well-described HOTS instruments, and experimental, quasi-experimental, or longitudinal evidence.

## **THEORETICAL BACKGROUND**

Integrated STEM education draws upon multiple conceptual frameworks designed to promote problem-solving, creativity, and interdisciplinary learning. One of the most prominent frameworks is the Engineering Design Process (EDP), which encourages learners to define problems, brainstorm solutions, prototype, and test their ideas. This iterative cycle mirrors real-world scientific and engineering practice and aligns with constructivist principles advocating for experiential learning (Azadboni & Torbati, 2025; Anastácio et al., 2022). EDP fosters deeper comprehension by engaging students in solving authentic challenges collaboratively, promoting critical thinking and systematic reasoning (Nasir et al., 2024; López et al., 2024).

Another widely adopted model is the 5E Learning Cycle—Engage, Explore, Explain, Elaborate, Evaluate—which supports inquiry-based learning and reinforces self-directed exploration (Çelikkanlı & Kızılcık, 2022; Begum et al., 2023). These models collectively underpin the pedagogical foundation for embedding HOTS into digital STEM instruction.

Constructivism remains central in explaining how learners build knowledge through digital interactions. Interactive digital modules that feature simulations, feedback loops, and real-time engagement are well-positioned to foster HOTS such as evaluation, synthesis, and application (Li et al., 2024; Martínez-Borreguero et al., 2024; Lee et al., 2022). Inquiry-based learning further reinforces HOTS by promoting curiosity, questioning, and reflective dialogue (Veith et al., 2025; Abril & Arévalo, 2024).

Additionally, the Cognitive Theory of Multimedia Learning, developed by Mayer, provides insights into how learners integrate visual and verbal information simultaneously.

This dual coding facilitates deeper conceptual understanding and supports higher-order processing, especially when instructional materials are well-segmented, signaled, and relevant (Volfson et al., 2023; Egri et al., 2025).

Historically, early digital learning relied on static e-modules composed primarily of text and images. These modules often lacked interactivity and failed to engage students in meaningful learning processes. The evolution toward interactive digital modules marked a pedagogical shift, introducing features such as simulations, embedded assessments, and adaptive feedback systems (Tuveri & Steri, 2024; Nurrisqi, 2025). These features allow learners to manipulate variables, visualize dynamic systems, and receive tailored instruction.

Moreover, adaptive learning systems go beyond interactivity by using data analytics to personalize content delivery based on students' performance and misconceptions (Kleinschmit et al., 2023; Kahaleh & López, 2025). This technological evolution aligns with student-centered learning paradigms, offering a more responsive and inclusive learning experience.

STEM education has moved beyond isolated subject instruction toward integrated, design-based pedagogies. This shift emphasizes solving real-world problems using knowledge from multiple disciplines. Project-based and inquiry-based learning models are now widely used to encourage collaboration and critical thinking (Persson, 2025; Steinwachs & Martens, 2025). For instance, programs integrating environmental science and engineering challenge students to apply diverse skill sets in authentic contexts (Liu et al., 2023; Beatty et al., 2023).

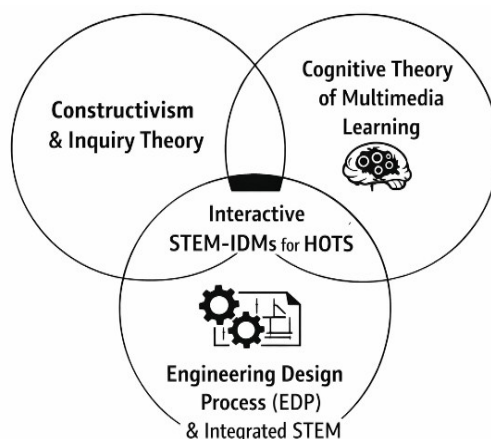
These interdisciplinary approaches reflect constructivist views where learners co-construct knowledge through collective inquiry and design tasks (Putri et al., 2022; Şengül, 2024). This paradigm aligns with 21st-century learning goals by cultivating transferable skills in creativity, reasoning, and systemic thinking.

While interactivity in digital modules is generally associated with increased engagement, its effect on learning depth and HOTS remains debated. Some scholars argue that interactivity can lead to surface-level engagement if not paired with cognitive scaffolding or reflection opportunities (Korur, 2025; Hermita et al., 2023; Carleschi et al., 2022). Learners might engage with simulations or multimedia elements without achieving conceptual mastery (Luan et al., 2025; Paçacı et al., 2023). This "activity trap" underscores the importance of pedagogical integration alongside technological design.

Another area of concern is the superficial application of STEM labels. Some digital modules claim interdisciplinary grounding but fail to implement genuine integration, particularly in aligning tasks with the Engineering Design Process or inquiry cycles. Authentic STEM integration requires coherence across learning goals, tasks, and assessments—not merely the inclusion of multiple subject terms (Azadboni & Torbati, 2025; Nasir et al., 2024).

Measuring HOTS within digital STEM contexts remains methodologically complex. Traditional tests often emphasize factual recall and do not capture analytical or evaluative reasoning (Kresin et al., 2024; Hartelt & Martens, 2025). Confounding variables such as learner background or digital literacy further complicate interpretation (Sundberg & Andersson, 2023; Volfson et al., 2023).

Although qualitative methods can capture richer data on cognitive processes, they pose challenges in standardization and scalability (Steinwachs & Martens, 2025; Şengül, 2024). Furthermore, as HOTS evolve with educational goals, assessment tools must be continually updated and validated (Jančaříková & Jančařík, 2022; Liu et al., 2023). Without rigorous tools, evaluations risk underreporting the true impact of STEM-integrated digital modules. A theoretical convergence model is used to illustrate the integration of constructivist and inquiry-based learning theory with the EDP, STEM frameworks, and cognitive theory of multimedia learning as the foundational architecture of HOTS. Figure 2 shows how a conceptual convergence models are developed using these framework's principles



**Figure 2.** Theoretical convergence model

Figure 2 presents a synopsis of the theoretical framework behind STEM-integrated interactive digital modules (IDMs) by highlighting the convergence of three complementary foundations: constructivist and inquiry-based learning theory, the EDP within integrated STEM education, and the cognitive theory of multimedia learning. By exploring and resolving problems with active knowledge construction, constructivism offers an epistemological basis, as illustrated in Figure 2. This is the case. The EDP provides a systematic, iterative process for solving problems that allows for the implementation of interdisciplinary reasoning in practical design situations. According to multimedia cognitive theory, carefully constructed visual and verbal representations enhance cognitive processing and facilitate deeper conceptual integration by reducing extraneous load. Effective STEM-IDMs are rooted in the pedagogical core of their intersectional framework, where technology is not just a delivery medium but also embodies cognitive design environments. This combination is key to this concept. The integration of inquiry processes, design-based iteration, and multimedia principles enables interactive modules to systematically engage analytical reasoning, evaluation, or synthesis, which are the fundamental components of higher-order thinking skills.

## RESULTS AND FINDINGS

### Models of STEM Integration Embedded in Interactive Digital Modules

This section synthesizes how STEM approaches are embedded within the structure of interactive digital modules (IDMs), focusing on integration models, learning design, and targeted Higher-Order Thinking Skills (HOTS). Table 1 presents a theme-specific subset of 12 studies from the final corpus of 22 studies covering diverse education levels and disciplinary contexts, with STEM integration operationalized through frameworks such as Inquiry-Based Learning (IBL), Engineering Design Process (EDP), mastery learning, and transdisciplinary digital storytelling. The table should be read together with the master study matrix, because the 12 studies represent evidence relevant to RQ1 rather than the entire review corpus.

Among the 12 studies, the EDP or problem-based structure appears most frequently, with 7 studies adopting inquiry-driven, iterative, or problem-context anchored designs (e.g., Sowanto & Hadi, 2026; Sariyatun et al., 2025; Hao & Chen, 2025). Digital modules in these studies embed structured learning cycles (Define, Design, Develop, Disseminate), reflecting STEM problem-solving paradigms aligned with constructivist learning theory, as demonstrated in studies such as Sowanto & Hadi. (2026), Sariyatun et al. (2025), and Hao & Chen (2025).

Several modules integrate STEM through cultural and contextual adaptation. For instance, Sowanto & Hadi (2026) designed ethnomathematics-infused modules using a 4D model tailored to junior high geometry, yielding measurable gains in problem-solving and spatial reasoning. Similarly, Zhou et al. (2025) implemented transmedia storytelling with VR/AR tools to deepen interdisciplinary reasoning and analytical engagement. Both cases

exemplify the shift toward context-rich, design-based STEM learning, as illustrated in studies by Sowanto & Hadi (2026) and Zhou et al. (2025), who each demonstrated the importance of embedding cultural and interdisciplinary contexts into the module design to support deeper conceptual understanding and analytical engagement.

A notable trend involves leveraging interactive technology for conceptual scaffolding and HOTS development. Bhagat et al. (2025) utilized immersive VR lessons based on Mayer's Cognitive Theory of Multimedia Learning, while Hao & Chen (2025) embedded ChatGPT into BOPPPS-model modules, resulting in an 18.4% improvement in applied reasoning scores. Because this percentage comes from a single AI-assisted module and a specific assessment context, it is interpreted as study-specific evidence rather than a pooled estimate across HOTS measures. These studies highlight how advanced digital formats can structurally embed cognitive demands within STEM content, as supported by Bhagat et al. (2025) and Hao & Chen (2025), who each employed immersive VR and AI-integrated participatory models, respectively, to structurally reinforce higher-order cognitive processes within interactive digital modules.

Science content integration varies across studies. Natural sciences (Smagulov et al., 2025; Asher et al., 2025) and engineering mathematics (Rzyankina et al., 2024) dominate the sample, with HOTS outcomes targeting analytical thinking, conceptual reasoning, and methodological competence. Modules typically included iterative task design, reflective cycles, and digital feedback loops, reflecting alignment with EDP stages, as evidenced in studies such as Smagulov et al. (2025), Asher et al. (2025), and Rzyankina et al. (2024), which demonstrated consistent implementation of digital feedback loops and reflective iterations aligned with the EDP learning cycle.

The depth of STEM integration ranges from multidisciplinary (e.g., Crocco et al., 2026) to interdisciplinary and transdisciplinary approaches (e.g., Varma et al., 2023; Zhou et al., 2025). In this review, multidisciplinary integration refers to modules that place STEM domains side by side, interdisciplinary integration refers to modules that connect disciplinary knowledge through structured inquiry or design tasks, and transdisciplinary integration refers to modules organized around authentic problems that require learners to move beyond disciplinary boundaries. Only 3 studies explicitly documented alignment of module tasks with national or curricular standards, indicating a common limitation in integration depth reporting.

Key constraints include scalability (Fadillah et al., 2023), technological access (Zhou et al., 2025), and teacher mediation variability (Smagulov et al., 2025). Nonetheless, studies most frequently reported positive HOTS-related outcomes in problem solving, analytical reasoning, and interdisciplinary engagement, particularly when module design is structured around inquiry cycles, authentic contexts, and iterative task models. However, these claims should be interpreted cautiously because the studies varied in design rigor, intervention duration, and HOTS measurement instruments.

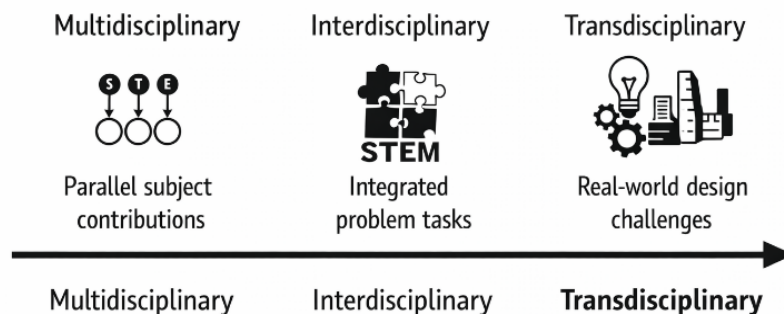
**Table 1.** Models of STEM Integration Embedded in Interactive Digital Modules

Study (Year)	Science Topic & Level	STEM Integration Model	Module Structure & Learning Design	HOTS Focus	Key Findings
(Sowanto & Hadi, 2026)	Geometry – Junior High	Ethnomathematics-integrated STEM contextualization.	4D model (Define–Design–Develop–Disseminate); culturally embedded digital tasks.	Problem-solving, spatial reasoning.	Significant improvement in geometry problem-solving; culturally contextualized digital modules enhance conceptual mastery.

Study (Year)	Science Topic & Level	STEM Integration Model	Module Structure & Learning Design	HOTS Focus	Key Findings
(Nungu et al., 2023)	STEM (Math & Science) – Postgraduate.	Online collaborative STEM with multimedia tools.	Small-group online collaboration; virtual labs; multimedia integration.	Knowledge co-construction, higher-order reasoning.	Positive correlation ( $r=0.69$ ) between cognitive presence and performance; multimedia tools support HOTS.
(Sariyatun et al., 2025)	History (Interdisciplinary inquiry) – High School.	Inquiry-Based Learning with digital primary sources.	Quasi-experimental digital materials; structured inquiry cycle.	Historical thinking, HOTS.	Significant gains in HOTS and analytical skills via inquiry-based digital materials.
(Rzyankina et al., 2024)	Engineering Mathematics – University.	Conceptual change framework + interactive e-textbook.	AI-enabled e-textbook with quizzes, multimedia, adaptive interaction.	Critical reasoning, conceptual understanding.	Improved conceptual reasoning and deeper mathematical understanding.
(Asher et al., 2025)	General Chemistry – University.	Mastery learning + digital resource integration.	Iterative digital testing cycles; structured self-regulated learning.	Analytical thinking, self-regulated problem solving.	Increased engagement with digital materials and higher final exam scores.
(Bhagat et al., 2025)	STEM Teacher Education – University.	360° VR grounded in Cognitive Theory of Multimedia Learning.	Immersive interactive VR lessons; educator-generated content.	Spatial reasoning, applied problem solving.	High usability; immersive VR enhances engagement and conceptual visualization.
(Crocco et al., 2026)	Multidisciplinary STEM – University.	H5P interactive content integration.	Faculty-designed HTML5 interactive modules embedded in LMS.	Analytical engagement, applied knowledge.	Enhanced engagement and improved learning outcomes across disciplines.
(Hao & Chen, 2025)	Machine Learning – Undergraduate.	BOPPPS model + ChatGPT-assisted AI integration.	Structured participatory model with AI-generated interactive content.	Deep thinking, applied AI reasoning.	18.4% grade increase; structured STEM-AI integration improves higher-order performance.
(Smagulov et al., 2025)	Natural Sciences – University.	Reflective ICT-supported STEM competence model.	Blended system with AR/VR, project work, reflective cycles.	Reflective thinking, methodological competence.	Improved digital competence, retention, and professional decision-making.
(Varma et al., 2023)	Physiotherapy (Applied Science) –	Blended & flipped STEM-integrated	Meta-analytic review of interactive websites &	Practical skill application, critical thinking	Interactive and blended approaches more effective than

Study (Year)	Science Topic & Level	STEM Integration Model	Module Structure & Learning Design	HOTS Focus	Key Findings
(Fadillah et al., 2023)	Higher Education. TVET (Technology & Engineering) – Vocational.	digital learning. Mobile learning with digital entrepreneurship integration.	flipped classrooms. Raspberry Pi-based mobile modules; project-oriented tasks.	Problem solving, applied technical reasoning.	traditional methods. Mobile-based modules support entrepreneurial and technical competence.
(Y. Zhou et al., 2025)	Cultural-Technology Integration – Higher Education.	Transmedia storytelling + digital STEM technologies.	VR/AR, interactive apps, multimedia storytelling platforms.	Analytical engagement, interdisciplinary reasoning.	Digital technologies expand interactive learning and deepen conceptual engagement.

Figure 3 displays the continuum of STEM integration depth in interactive digital modules, showing the progression from multidisciplinary to interdisciplinary and transdisciplinary models and its conceptual connection to higher-order thinking activation. The figure is an author-derived synthesis model based on the coding of STEM integration depth in Table 1. Figure 3 shows the difference between multidisciplinary integration, where disciplines work alongside each other with little conceptual mixing, and interdisciplinary models, which link knowledge areas through organized inquiry or Engineering Design Process cycles. Across all domains of study, transdisciplinary approaches place learning within genuine, practical design dilemmas where problem-based reasoning prevails over disciplinary boundaries. The effectiveness of IDMs in enhancing higher-order thinking skills (HOTS) is not solely determined by the presence of various STEM components, but rather by their integration into one another across different domains. The reviewed studies suggest that modules using iterative design tasks, contextualized inquiry, and authentic problem-solving were more likely to activate analytical reasoning, evaluation, and problem-solving than modules with loosely connected STEM content. Figure 3 presents a structural perspective for interpreting the diverse integration models in Table 1, which connect to cognitive activation through pedagogical architecture.



**Figure 3.** The continuum of STEM integration depth in interactive digital modules

### Digital Module Design Features That Promote Higher-Order Thinking Skills (HOTS)

This section examines the design features embedded in interactive digital modules (IDMs) that support the development of Higher-Order Thinking Skills (HOTS). Table 2 synthesizes the structural, pedagogical, and technological design elements reported across a theme-specific subset of 11 studies, with each module explicitly targeting cognitive growth via

scaffolding, multimodal interactivity, real-time feedback, or personalization. These 11 studies are not presented as a separate review sample; rather, they are the studies from the final corpus that provided sufficient information on IDM design mechanisms relevant to RQ2.

Nine of the 11 studies (81.8%) employed multimodal content presentation of the 11 studies—integrating animations, video, audio narration, and simulations—to enhance cognitive processing and concept retention. For example, Neyem et al. (2025) and Bhagat et al. (2025) demonstrated how such multimodal features improve students' visual-spatial reasoning and comprehension through immersive environments. These findings align with Mayer's Cognitive Theory of Multimedia Learning, reinforcing the value of dual-channel learning pathways. However, multimodality was interpreted as a design affordance rather than direct evidence of HOTS unless accompanied by validated or clearly described HOTS measures.

Adaptive feedback and diagnostic assessments appeared in six studies (54.5%). Ma et al. (2024) and Hidayati et al. (2025) utilized formative quizzes with real-time analytics to tailor learning paths. Hao & Chen (2025), who integrated ChatGPT into their digital module, observed an 18.4% improvement in students' applied reasoning outcomes—a result that suggests the potential of AI-supported scaffolding but should not be generalized across all IDM formats because the outcome measure and learning context were study-specific.

Cognitive scaffolding and metacognitive prompts featured in seven studies (63.6%). For instance, Zhou et al. (2025) and Syahfutra et al. (2024) included embedded reflective questions and learning journals that encouraged evaluative thinking and strategic learning behavior. These design components promote active knowledge construction and have been tied to enhanced analytical engagement. In the synthesis, metacognitive prompts were treated as mechanisms that support HOTS rather than as HOTS outcomes unless the original study explicitly measured analysis, evaluation, creation, reasoning, or problem-solving.

Simulation-based inquiry was used in five studies (45.5%). Modules developed by Xu & Zhou (2022) and Smagulov et al. (2025) incorporated virtual labs or AR/VR-based explorations, allowing students to manipulate variables and test hypotheses—critical for developing analytical and problem-solving skills. Moreover, four studies (36.4%) included collaborative features such as shared digital workspaces or discussion boards. In Nungu et al. (2023), such collaboration correlated with cognitive presence ( $r = 0.69$ ), suggesting the value of peer interaction in stimulating HOTS. Because this association is correlational, it was not interpreted as causal evidence.

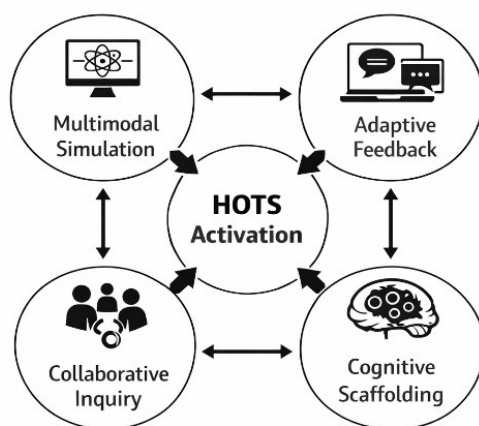
Self-regulated learning tools, such as progress trackers, digital journals, or time-management prompts, were reported in five studies. For example, Rzyankina et al. (2024) and Neyem et al. (2025) employed interactive dashboards that empowered students to monitor their own progress, enhancing autonomy and reflective learning. Overall, the findings indicate a recurring pattern rather than a definitive consensus: multimodal interactivity, adaptive feedback, and scaffolded inquiry were the most frequently reported design elements associated with HOTS-related outcomes in STEM-IDMs. These components, particularly when guided by constructivist and inquiry-based learning theories, support deep engagement and cognitive development.

**Table 2.** Digital Module Design Features That Promote Higher-Order Thinking Skills (HOTS)

Study (Year)	Interactive Design Features Used	Cognitive/Theoretical Justification	HOTS Promoted	Outcomes Reported
(Bhagat et al., 2025)	360° VR immersion, multimodal content, embedded decision nodes.	Cognitive Theory of Multimedia Learning.	Applied problem solving, analytical reasoning.	Immersive VR increased visualization accuracy and reasoning speed.

Study (Year)	Interactive Design Features Used	Cognitive/Theoretical Justification	HOTS Promoted	Outcomes Reported
(Hao & Chen, 2025)	ChatGPT-generated prompts, adaptive quizzes, feedback scaffolding.	AI-based personalized learning.	Deep reasoning, application of machine learning.	18.4% improvement in applied reasoning scores.
(Y. Zhou et al., 2025)	Transmedia storytelling, embedded reflection questions, AR/VR content.	Constructivist theory, metacognition.	Analytical engagement, interdisciplinary thinking.	Digital storytelling enhanced reflection and interdisciplinary synthesis.
(Neyem et al., 2025)	Simulation-based inquiry, interactive videos, student control options.	Inquiry-based learning, dual processing.	Experimental reasoning, visual-spatial analysis.	Higher visual reasoning and experimental accuracy in post-tests.
(Xu & Zhou, 2022)	Simulation labs, inquiry tasks, real-time feedback, student modeling.	Problem-based learning, scaffolding.	Causal inference, hypothesis testing.	Students showed better conceptual integration and variable manipulation skills.
(Ma et al., 2024)	Diagnostic quizzes, performance analytics, personalized feedback reports.	Formative assessment, learner analytics.	Reflective learning, metacognitive regulation.	Personalized feedback improved learning strategies and self-assessment skills.
(Hidayati et al., 2025)	Adaptive assessments, embedded hints, real-time feedback loops.	Differentiated instruction, scaffolding.	Strategy use, conceptual regulation.	Improved strategy transfer and conceptual clarity.
(Syahfutra et al., 2024)	Interactive e-module, digital journaling, self-assessment tasks.	Self-regulated learning, reflective thinking.	Evaluation, reflective analysis.	Higher self-regulation scores and engagement.
(Nungu et al., 2023)	Multimedia-enhanced collaboration boards, online peer review forums.	Social constructivism, cognitive presence.	Knowledge co-construction, critical thinking.	Positive correlation ( $r = 0.69$ ) between collaboration and higher-order engagement.
(Rzyankina et al., 2024)	Interactive e-textbook, dashboard analytics, feedback-guided pathways.	Conceptual change theory, metacognition.	Conceptual understanding, analytic tracking.	Greater understanding of core engineering principles.
(Smagulov et al., 2025)	Blended AR/VR projects, iterative design journals, reflective questioning.	Inquiry cycles, design-based learning.	Scientific reasoning, evaluative judgment.	Enhanced retention, digital competence, and evaluative reasoning.

Digital modules that integrate STEM and Core interactive design mechanisms jointly activate higher-order thinking skills (HOTS) through multimodal simulation, adaptive feedback, cognitive scaffolding, and collaborative inquiry.



**Figure 4.** The Core interactive design mechanisms within STEM-integrated digital modules

The central design mechanisms identified in the reviewed studies of STEM-integrated interactive digital modules (IDMs) are shown in Figure 4. These mechanisms act as drivers of higher-order thinking skills. The four interrelated components, multimodal simulation, adaptive feedback, cognitive scaffolding, and collaborative inquiry, work together to encourage deep cognitive engagement. Multimodal simulations help students visualize abstract scientific phenomena, manipulate variables, and engage in dynamic simulation activities that promote analytical thinking and hypothesis testing. Adaptive feedback systems improve metacognitive regulation and help with conceptual refinement by providing prompt corrective input and personalized guidance. By using cognitive scaffolding such as structured prompts and a staged inquiry sequence, learners can navigate complex problem-solving tasks without excessive cognitive load. In the meantime, collaborative inquiry environments foster knowledge co-construction and evaluative dialogue, which strengthens interdisciplinary reasoning. Figure 4 illustrates that these mechanisms do not operate independently, but their alignment determines the intensity and duration of activation in HOTS. Thus, Figure 4 should be interpreted as an author-derived conceptual synthesis of the design mechanisms reported in Table 2, not as a separately tested causal model.

### **Effectiveness of STEM-Integrated Interactive Modules on Higher-Order Thinking Skills (HOTS)**

This section evaluates the effectiveness of STEM-integrated interactive digital modules (IDMs) in promoting HOTS outcomes, as detailed in Table 3. The synthesis draws from a theme-specific subset of 11 studies employing varied assessment instruments, design models, and educational settings, ranging from high school to university levels. These studies were included in this subsection because they reported measurable HOTS-related outcomes, but their evidence strength varied according to research design, measurement validity, and whether outcomes were immediate, retained, or transferred.

Nine of the 11 studies (81.8%) reported positive effects or improvements in HOTS-related indicators, although not all studies used equivalent instruments or reported statistical significance in the same way. For example, Hao & Chen (2025) found an 18.4% increase in post-test scores on applied reasoning among undergraduate students engaged in a ChatGPT-assisted BOPPPS module. Similarly, Bhagat et al. (2025) reported increased analytical reasoning speed and spatial visualization accuracy following immersive VR-based STEM instruction. Therefore, the 18.4% figure was treated as a study-specific result rather than a general effect size for AI-supported STEM-IDMs.

Experimental studies dominated the review, with seven employing quasi-experimental or true experimental designs. Zhou et al. (2025) used a pre-post test model to show gains in interdisciplinary thinking, while Manolov (2025) demonstrated improved analytical outcomes through structured project-based digital modules in physics learning. Modules embedding

inquiry cycles and iterative tasks—like those by Sariyatun et al. (2025) and Xu & Zhou (2022)—reported greater impact on hypothesis testing, conceptual integration, and evaluative reasoning. However, because the studies differed in comparison groups, intervention duration, and instrument validation, the effectiveness claims are presented as effect-direction synthesis rather than meta-analytic estimates.

The choice of assessment tools varied across studies. Neyem et al. (2025) used HOTS-specific pre-post diagnostics, while Ma et al. (2024) deployed learner analytics dashboards to track reflective strategies and self-regulated performance. Qualitative instruments, such as think-aloud protocols used by Bukhari et al. (2025) and digital journaling used by Syahfutra et al. (2024), complemented quantitative tools in five studies, enabling a multi-dimensional evaluation of HOTS. Nevertheless, the validation status of these instruments was not consistently reported, making it necessary to distinguish standardized or validated HOTS tests from author-made rubrics, analytics indicators, journals, and reflective data.

Four (36.4%) of the 11 studies measured retention or transfer beyond the immediate post-test, although the follow-up period was generally short. For instance, Smagulov et al. (2025) assessed digital competence and reasoning three weeks post-intervention, revealing sustained HOTS gains. Similarly, Sowanto & Hadi (2026) observed improved cultural contextualization and spatial reasoning in delayed assessments. Accordingly, the evidence supports short-term retention more clearly than long-term transfer.

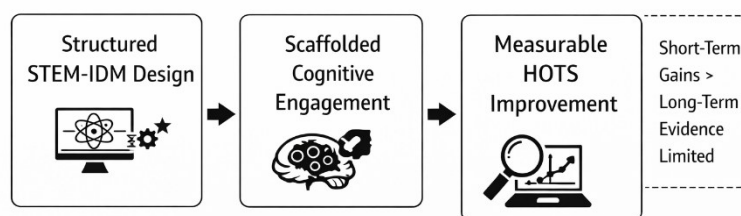
Six studies (54.5%) emphasized the role of instructional scaffolding—either cognitive, metacognitive, or technological—in sustaining HOTS performance. These include Syahfutra et al. (2024), who embedded self-assessment tasks in a digital science module, and Hidayati et al. (2025), whose adaptive assessments fostered conceptual regulation. Overall, the evidence suggests a generally positive short-term effect direction of STEM-integrated IDMs on HOTS outcomes, particularly when scaffolded instruction, multimodal content, and inquiry-based activities are effectively aligned with the module’s cognitive objectives. The strongest evidence was found in studies with experimental or quasi-experimental designs and explicit HOTS measures, whereas qualitative reflections and learner analytics were used primarily to explain learning processes.

**Table 3.** Effectiveness of STEM-Integrated Interactive Modules on Higher-Order Thinking Skills

Study (Year)	Research Design & Instruments Used	Target HOTS Outcomes	Key Results	Duration/Retention Testing
(Hao & Chen, 2025)	Quasi-experimental; pre-post HOTS test.	Applied reasoning, analytical thinking.	18.4% improvement in post-test scores.	Immediate post-test only
(Bhagat et al., 2025)	Mixed-methods; spatial HOTS test + usability survey.	Spatial reasoning, analytical speed.	Enhanced reasoning speed and visualization accuracy.	Short-term retention
(Y. Zhou et al., 2025)	Pre-post design; interdisciplinary HOTS rubrics.	Analytical synthesis, interdisciplinary reasoning.	Gains in interdisciplinary HOTS scores.	No follow-up
(Neyem et al., 2025)	Experimental; HOTS-specific diagnostics.	Experimental reasoning, problem-solving.	Higher accuracy in HOTS-related assessments.	Immediate gains only
(Xu & Zhou, 2022)	Quasi-experimental; inquiry task rubrics.	Hypothesis testing, conceptual integration.	Conceptual reasoning improved through simulation labs.	Gains retained 2 weeks
(Bukhari et al., 2025)	Qualitative; think-aloud protocol + open-ended reflections.	Analytical reasoning, reflective thinking.	Student reflections revealed complex reasoning patterns.	Not measured

Study (Year)	Research Design & Instruments Used	Target HOTS Outcomes	Key Results	Duration/Retention Testing
(Smagulov et al., 2025)	Longitudinal; pre-post + retention test.	Evaluative thinking, digital competence.	Sustained HOTS gains over 3-week interval.	Yes – 3 weeks post-test
(Manolov, 2025)	Quasi-experimental; HOTS rubric + learning outcomes.	Analytical thinking, argument construction.	Structured digital PBL improved HOTS and content mastery.	Immediate test only
(Syahfutra et al., 2024)	Pre-post + journaling analysis.	Reflective analysis, metacognition.	Increased metacognitive awareness and evaluation skills.	No follow-up
(Hidayati et al., 2025)	Mixed-methods; adaptive assessments + survey.	Conceptual regulation, strategic learning.	Enhanced strategy use and conceptual transfer.	Not specified
(Sowanto & Hadi, 2026)	Pre-post with cultural contextual HOTS tasks.	Spatial reasoning, contextual analysis.	Improved cultural contextual HOTS and geometry performance.	Yes – delayed test 2 weeks after intervention

Using structured STEM-integrated interactive digital module design, Figure 5 shows the conceptual pathway that leads to scaffolded cognitive engagement and observable improvements in higher-order thinking skills (HOTS), with evidence indicating short-term gains rather than long-term transfer. Figure 5 illustrates the empirical patterns observed across the reviewed studies by illustrating a conceptual progression from structured STEM-IDM design to measurable improvements in higher-order thinking skills HOTS. The illustration shows that inquiry cycles, Engineering Design Process (EDP) structures, adaptive feedback systems, and multimodal simulations form the foundation for scaffolded cognitive engagement. This engagement includes iterative reasoning, considering ideas from multiple perspectives, and metacognitive regulation. The mediating mechanism of scaffolded engagement supports the translation of design features into observable improvements in applied reasoning, analytical thinking, hypothesis testing, and evaluative judgment. The pathway is supported most directly by the studies reporting immediate or short-term improvements in Table 3, including Hao & Chen (2025), Xu & Zhou (2022), Smagulov et al. (2025), and Sowanto & Hadi (2026). However, because follow-up periods were limited to short intervals in only a few studies, Figure 5 should be interpreted as a synthesis model of short-term evidence rather than proof of durable long-term transfer.



**Figure 5.** Conceptual pathway of STEM-integrated interactive digital module design

**Challenges and Limitations in Implementing STEM-Based Interactive Digital Modules**

This section explores key challenges identified in the implementation of STEM-based interactive digital modules (IDMs), as detailed in Table 4. The findings synthesize insights from a theme-specific subset of 11 studies, highlighting recurring issues related to infrastructure, pedagogical preparedness, design coherence, and curriculum alignment. These studies were coded for RQ4 because they reported implementation barriers, scalability

concerns, or equity-related constraints; they are therefore interpreted primarily as contextual and implementation evidence rather than direct effectiveness evidence.

Technological infrastructure was the most frequently cited constraint, reported in six of the 11 studies (54.5%). For instance, Nor & Halim (2023) and Okwara & Pretorius (2023) noted the limited access to reliable internet and digital devices in underserved schools, creating a digital divide that hampers equitable adoption. Zhou & Bakhir (2024) also emphasized hardware limitations and inconsistent digital access in rural contexts, which restricted the functionality of AR/VR-rich modules. These findings indicate that access conditions may moderate the effectiveness of STEM-IDMs, particularly when modules require high-bandwidth platforms, VR/AR hardware, or continuous online interaction.

Teacher readiness and digital pedagogy were reported as challenges in five studies (45.5%). Both Mohseni et al. (2023) and Skurat Harris & Greer (2022) highlighted that insufficient professional development in integrating interdisciplinary content and emerging technologies hindered the pedagogical effectiveness of IDMs. The issue was further reinforced by Yang & Chen (2024), who noted that teachers lacked confidence in facilitating inquiry-based tasks using digital platforms. Thus, teacher mediation should be treated as a contextual moderator in the interpretation of HOTS outcomes rather than as a peripheral implementation issue.

Three studies (27.3%) pointed to design incoherence or lack of systematic instructional alignment. Porter et al. (2022) and Rahadiani et al. (2024) found that some modules suffered from poor integration between content and digital features, resulting in superficial engagement with STEM processes. Veselinović et al. (2025) echoed this concern, citing design inconsistency as a factor leading to cognitive overload and fragmented learning experiences. This finding supports the need to distinguish genuine integrated STEM-IDMs from digital resources that contain interactive features but lack coherent inquiry, design, or assessment alignment.

Curricular misalignment was identified in four studies (36.4%). For instance, Skurat Harris & Greer (2022) and Nor & Halim (2023) noted discrepancies between IDM content and national STEM curricula, leading to reduced classroom applicability. This misalignment often constrained the use of interactive features due to time or content restrictions imposed by standardized assessment frameworks. Accordingly, curriculum alignment should be reported not only as an implementation challenge but also as a criterion for judging the practical scalability of STEM-IDMs.

Scalability was mentioned in three studies, including Yang & Chen (2024), who documented logistical difficulties in extending VR-based modules to multiple classrooms. Mohammadi et al. (2025) observed similar challenges in scaling digital design platforms across different educational contexts. Despite these constraints, several studies reported partial mitigation strategies. Xu & Zhou (2022) implemented cloud-based simulation labs to reduce hardware dependency, while Vilppola et al. (2022) suggested modular training for teachers to scaffold digital pedagogy progressively. Overall, the findings suggest that although STEM-integrated IDMs hold great promise for enhancing HOTS, their successful implementation is contingent on addressing infrastructure inequities, strengthening teacher capacity, ensuring instructional coherence, and aligning content with curricular standards. The evidence for scalability and equity remains less developed than the evidence for short-term learning outcomes.

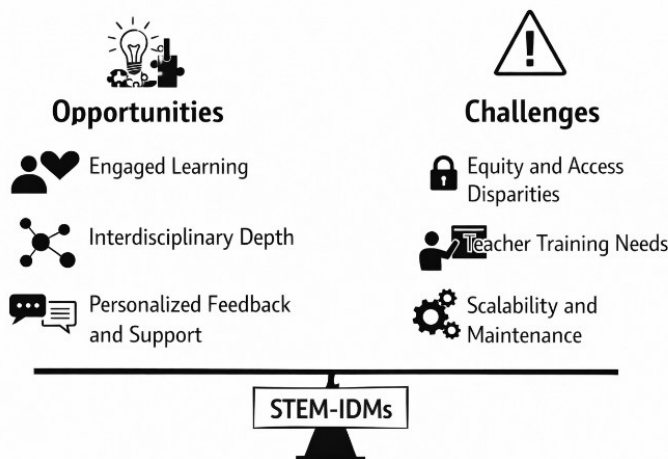
**Table 4.** Challenges and Limitations in Implementing STEM-Based Interactive Digital Modules

Study (Year)	Type of Limitation Identified	Context / Setting	Specific Constraints	Suggested Mitigations / Comments
(Nor & Halim, 2023)	Infrastructure, Curriculum alignment	Malaysian Secondary Schools.	Weak internet, device access;	Suggested localized content design and

Study (Year)	Type of Limitation Identified	Context / Setting	Specific Constraints	Suggested Mitigations / Comments
(Zhou & Bakhir, 2024)	Infrastructure, Teacher readiness	Rural China – Vocational Schools.	mismatch with STEM curriculum. Limited devices; untrained teachers in interdisciplinary module use.	mobile-friendly platforms. Highlighted need for rural tech support and training.
(Mohseni et al., 2023)	Teacher readiness, Curriculum coherence	German Upper Secondary.	Teachers lacked interdisciplinary teaching skills.	Recommended teacher workshops on digital STEM pedagogy.
(Skurat Harris & Greer, 2022)	Pedagogical, Curricular alignment	East Asia – Secondary Level.	Difficulty aligning VR content with national standards.	Urged co-design with curriculum developers.
(Yang & Chen, 2024)	Teacher readiness, Scalability	Chinese Science Classrooms.	Teachers unprepared for inquiry-based VR modules; large-scale deployment limits.	Emphasized phased implementation with digital mentorship.
(Mohammadi et al., 2025)	Design limitation, Scalability	European Maker Education Settings.	Fragmented design features; issues with scaling platforms.	Proposed universal design templates.
(Rahadiani et al., 2024)	Instructional coherence	Indonesian STEM e-Modules.	Misaligned activities with HOTS goals.	Encouraged integrated instructional mapping.
(Porter et al., 2022)	Design inconsistency	STEM Learning Modules in Brazil.	Unstructured digital sequencing; cognitive overload.	Recommended design standardization and usability testing.
(Okwara & Pretorius, 2023)	Infrastructure	Sub-Saharan Africa – Urban-Rural Divide.	Low-cost schools lacked devices, bandwidth.	Proposed community-based tech sharing initiatives.
(Xu & Zhou, 2022)	Infrastructure, Implementation constraints	Online Simulation Labs (Pilot).	Browser-based tools limited in low-bandwidth areas.	Used compressed simulation formats and cloud delivery.
(Vilppola et al., 2022)	Teacher training gaps	STEM PD Program (Multi-country).	Teachers resisted tech integration; low confidence in digital facilitation.	Proposed modular training units and peer coaching.

In Figure 6, interactive digital modules that incorporate STEM concepts face several contextual limitations, such as infrastructure issues, teacher readiness, curricular alignment challenges, and scalability obstacles. The implementation challenges common to the RQ4 evidence subset are outlined in a structured barrier framework for the adoption of STEM-IDM as shown in Figure 6. As illustrated here, infrastructure constraints such as insufficient internet bandwidth and limited device availability create a major structural barrier to equitable access. The teacher readiness factor adds a second crucial aspect, which includes deficiencies in interdisciplinary pedagogical skills, digital facilitation confidence, and professional development opportunities. The challenges associated with curriculum alignment hinder implementation, especially when the content of interactive modules does not match national standards or assessment structures. Scalability challenges, particularly in resource-intensive

environments like AR/VR-supported modules, limit the adoption of broader institutional deployment. This framework emphasizes that these factors are not independent variables; deficiencies in one aspect can lead to weaknesses that increase difficulties in others. Figure 6 provides a comprehensive perspective on why successful instructional designs may not always result in sustained, large-scale impact, by organizing the constraints illustrated below. Therefore, addressing these contextual barriers is crucial to ensure that STEM-integrated interactive digital modules achieve durable and equitable HOTS development. As with Figures 3–5, Figure 6 is an author-derived synthesis model based on the implementation barriers coded in Table 4.



**Figure 6.** Framework of STEM-integrated interactive digital modules

## DISCUSSION

The systematic review of STEM-integrated interactive digital modules (IDMs) indicated generally positive but uneven evidence regarding their effectiveness in promoting Higher-Order Thinking Skills (HOTS) when well-designed and contextually implemented. Evidence was strongest for short-term HOTS-related performance in small-scale experimental and quasi-experimental studies, while evidence for long-term transfer, scalability, and equity remained limited. The conversion of interactive engagement into measurable HOTS gains is facilitated by specific mechanisms, as shown across Tables 1 to 4 and supported by theoretical models discussed earlier.

One key mechanism is interactive engagement. Studies such as Hao & Chen (2025) and Bhagat et al. (2025) from Table 3 demonstrated significant post-intervention gains in analytical reasoning and spatial visualization, suggesting that student interaction with dynamic, technology-driven environments can support HOTS development. Zhou et al. (2025) also revealed that interdisciplinary digital storytelling could facilitate analytical synthesis when students engage with interactive, multimedia-rich content. These findings align with Ma et al. (2022), who highlighted how interactive STEM learning environments stimulate cognitive development through hands-on exploration. However, these outcomes should be interpreted in relation to the specific instruments, intervention duration, and study designs used in each study.

Second, learning engagement plays a mediating role. Table 2 reveals that modules integrating simulations, gamified platforms, and exploratory tasks—such as those by Xu & Zhou (2022) and Skurat Harris & Greer (2022)—were associated with deeper cognitive immersion. These findings resonate with Li (2025) and Huang et al. (2024), who assert that learner engagement is related to cognitive growth and HOTS acquisition, especially in virtual environments. Nevertheless, engagement should be treated as a mediating condition rather than direct evidence of HOTS unless higher-order outcomes are explicitly measured.

Feedback and reflection mechanisms further enhance learning outcomes. For instance, modules with adaptive assessment features (Hidayati et al., 2025) and reflective journaling

tasks (Syahfutra et al., 2024) provided students with continuous feedback loops, reinforcing analytical and evaluative skills. This is consistent with Edison's findings that structured feedback in AI-integrated media may contribute to HOTS development (Edison, 2025). However, feedback-related claims should be linked to the quality of the assessment instrument and whether the measured outcome reflects analysis, evaluation, creation, or problem-solving rather than general engagement.

Scaffolding emerged as another consistent contributor. Studies such as Syahfutra et al. (2024) and Ma et al. (2024) demonstrated that embedded supports, like metacognitive prompts and adaptive dashboards, enabled students to navigate complex STEM tasks more confidently. This supports Lee et al. (2023), who emphasized the effectiveness of phased scaffolding techniques in building HOTS competencies. In this review, scaffolding is interpreted as a design mechanism that supports HOTS activation, while metacognition and self-regulation are treated as supporting processes unless the original studies directly assessed higher-order cognitive performance.

The effectiveness of these mechanisms, however, is moderated by contextual factors. Teacher facilitation remains pivotal. Zhou & Bakhir (2024) and Yang & Chen (2024) from Table 4 showed that teachers' ability to guide digital inquiry and adapt STEM content is crucial to IDM success, reflecting the importance of pedagogical mediation as described by Mustapha & Abdullah (2024). Learner prior knowledge also influenced outcomes, as seen in Smagulov et al. (2025) and Sowanto & Hadi (2026), where students with baseline competencies demonstrated sustained HOTS improvement. This aligns with Nasution (2025) and Sofyan et al. (2025), who reported enhanced gains in students with foundational STEM readiness. Thus, teacher readiness, learner preparedness, and implementation context should be treated as moderators of effectiveness rather than background variables.

Duration of exposure to IDMs also shaped learning depth. Xu & Zhou (2022) and Smagulov et al. (2025) reported short-term retention evidence weeks after module use, reinforcing findings by Deno (2025) and Ginting et al. (2024), which advocate for extended interventions to foster durable cognitive transformation. Nevertheless, the review uncovered several critical evidence gaps. While immediate HOTS gains were widely reported, few studies (e.g., Smagulov et al. (2025); Sowanto & Hadi, 2026)) assessed long-term knowledge transfer, echoing the meta-analysis by Wang et al. (2025), which calls for deeper longitudinal analysis (Wang et al., 2025). Furthermore, scalability remains underexplored. As Zhou & Bakhir (2024) and Mohammadi et al. (2025) indicated, infrastructural and logistical barriers impede broader adoption. This concern is amplified by Shamonina & Семеніхіна (2025), who highlight cross-national disparities in STEM implementation. Consequently, the evidence base is more defensible for immediate and short-term outcomes than for durable transfer across contexts.

Equity challenges were also apparent. Nor & Halim (2023) and Okwara & Pretorius (2023) underscored digital divides in access to devices and connectivity. These findings align with Bukhari et al. (2025) and Garrison et al. (2022), who emphasize socio-cultural and gender inequities that affect STEM participation. To address these challenges, several design principles are recommended. Inclusive design, as advocated by Yoon et al. (2025), is essential for equitable STEM module delivery. Modules should support collaboration, as highlighted by Asrizal et al. (2022), with built-in peer interaction and teamwork functions. Continuous assessment mechanisms should be standard features (Edison, 2025; N. Ma et al., 2024). Equally, robust teacher training must be institutionalized to ensure pedagogical readiness (Chatmaneerungcharoen, 2024; Skurat Harris & Greer, 2022). These recommendations should be interpreted as implementation implications derived from recurring barriers, not as evidence that such strategies have already been validated at scale.

At the policy level, funding strategies should prioritize infrastructure in underserved schools (Utha & Pem, 2025). Multi-stakeholder collaborations, such as CLix (Obaje et al., 2023), can facilitate resource pooling and teacher capacity building. Lastly, policies must

support data-driven module refinement, as emphasized by Asrizal et al. (2022), ensuring evidence-based scaling and innovation in STEM learning environments. The original contribution of this review lies in integrating four analytic dimensions—STEM integration depth, interactive design mechanisms, evidence strength, and implementation barriers—into a framework for interpreting how IDMs may support HOTS in science education. In conclusion, while STEM-integrated interactive digital modules present substantial but context-dependent potential for HOTS development, their effectiveness hinges on deliberate design, sustained teacher support, equitable implementation, and long-term policy commitment.

## CONCLUSION

This systematic literature review examined the integration of STEM approaches into interactive digital modules and their relation with Higher-Order Thinking Skills (HOTS) in science education. Across the synthesized evidence, STEM-embedded digital modules showed the most consistent short-term potential to support analytical reasoning, evaluative judgment, problem-solving, and interdisciplinary thinking when grounded in structured pedagogical frameworks such as the Engineering Design Process and inquiry-based learning.

The findings underscore that interactivity alone does not guarantee HOTS development. Rather, meaningful gains emerge when interactive features are strategically aligned with cognitive scaffolding, authentic problem contexts, adaptive feedback, and collaborative learning opportunities. Modules incorporating iterative design cycles, reflective prompts, and real-time assessment mechanisms showed the most defensible evidence for immediate and short-term HOTS-related outcomes, although evidence for sustained long-term transfer remains limited.

Despite promising results, several gaps persist. Long-term transfer of HOTS beyond immediate post-intervention assessments remains underexplored. Scalability challenges related to infrastructure, teacher preparedness, and contextual adaptation limit broader implementation. Equity issues—particularly digital divides and socio-cultural barriers—also require systematic policy attention. These gaps indicate that the evidence base is stronger for small-scale instructional effectiveness than for large-scale, equitable, and durable implementation.

Future research should prioritize longitudinal studies assessing transfer and retention, cross-context comparative trials, and rigorous measurement frameworks for HOTS. Additionally, adaptive and AI-enhanced scaffolding systems warrant further exploration to personalize learning pathways effectively. Policymakers and educational leaders must support sustained investment in digital infrastructure, inclusive design standards, and professional development to ensure equitable and scalable STEM innovation. In practical terms, the review suggests three evidence-aligned priorities: strengthening EDP- and inquiry-based module design, embedding multimodal simulation with adaptive feedback and scaffolding, and preparing teachers to mediate digital STEM inquiry in diverse classroom contexts.

In conclusion, integrating STEM approaches into interactive digital modules offers a promising but context-dependent pathway for advancing higher-order thinking in science education. However, achieving its full potential depends on coherent instructional design, empirical rigor, inclusive implementation, and long-term strategic commitment. The main contribution of this review is its integrative framework, which links STEM integration depth, interactive design mechanisms, contextual moderators, and HOTS outcomes to guide future research and implementation.

## RECOMMENDATION

Based on the findings of this systematic review, future research should move beyond short-term effectiveness testing and focus on longitudinal, cross-context, and methodologically rigorous studies of STEM-integrated interactive digital modules that explicitly target sustained HOTS development. Future studies should prioritize EDP-based and inquiry-driven module

designs enriched with adaptive feedback and AI-assisted scaffolding. Rather than treating immediate post-test gains as sufficient evidence, longitudinal quasi-experimental or mixed-methods designs should be used to examine retention, transfer, and implementation fidelity across diverse educational contexts. Validated HOTS assessment instruments, performance-based tasks, and learning analytics data are also needed to triangulate cognitive growth more rigorously.

However, several potential obstacles may influence research outcomes and should be treated as key design considerations rather than secondary implementation issues. First, variability in teacher facilitation and digital pedagogical competence may moderate the effectiveness of the intervention, potentially confounding results. Second, infrastructural disparities—such as limited internet access or device availability—may affect implementation fidelity, particularly in under-resourced schools. Third, differences in students' prior knowledge and digital literacy levels could influence the magnitude of HOTS gains. To mitigate these risks, future research and implementation programs should include teacher training sessions, baseline competency assessments, standardized implementation protocols, and monitoring mechanisms to ensure consistency and reliability of findings. For practice and policy, this review recommends sustained investment in digital infrastructure, inclusive module design, curriculum-aligned STEM tasks, and professional development that prepares teachers to facilitate inquiry-based digital STEM learning.

#### ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by *Hibah Risetmu Batch IX – Skema Penelitian Terapan Tahun Anggaran 2025 (No. 0259.009/I.3/D/2025)*, which made this research possible. This funding significantly contributed to the development, implementation, and analysis phases of the study. The authors sincerely appreciate the commitment to advancing applied research and innovation in education through this competitive grant program.

#### FUNDING INFORMATION

This research was funded by *Hibah Risetmu Batch IX – Skema Penelitian Terapan Tahun Anggaran 2025*, under grant number 0259.009/I.3/D/2025.

#### AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Rahmawati	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Tri Hastiti Fiskawarni	✓	✓	✓	✓			✓	✓		✓	✓			
Andi Arie Andriani	✓	✓	✓		✓	✓	✓		✓					
Widiasih	✓	✓		✓			✓							

#### CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

#### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

#### REFERENCES

- Asher, M. W., Hartman, J. D., Blaser, M., Eichler, J. F., & Carvalho, P. F. (2025). The promise of mastery-based testing for promoting student engagement, self-regulated learning, and performance in gateway STEM courses. *Computers & Education*, 237, 105387. <https://doi.org/10.1016/j.compedu.2025.105387>
- Asrizal, A., Zan, A. M., Mardian, V., & Festiyed, F. (2022). The Impact of Static Fluid E-Module by Integrating STEM on Learning Outcomes of Students. *Journal of Education Technology*, 6(1), 110–118. <https://doi.org/10.23887/jet.v6i1.42458>
- Bhagat, K. K., Wang, T., Kumar Jha, N., & Lampropoulos, G. (2025). 360 VR (virtual reality) Educator: Transforming teachers into interactive content creators. *Australasian Journal of Educational Technology*, 41(3), 62–83. <https://doi.org/10.14742/ajet.10145>

- Bukhari, S., Mureed, R., Rafiq-uz-Zaman, M., Shah, H., & Asghar, S. (2025). From Stereotypes to STEM Careers: A Mixed-Methods Study of Gender Bias and Female Self-Efficacy in Pakistani Universities. *ACADEMIA International Journal for Social Sciences*, 4(4), 195–214. <https://doi.org/10.63056/acad.004.04.0874>
- Chatmaneerungcharoen, S. (2024). Collaborative Professional Development for Science, Technology, and Mathematics Teachers in Designing iPad-integrated Lesson Plans. *Multidisciplinary Reviews*, 8(6), 2025170. <https://doi.org/10.31893/multirev.2025170>
- Clark, T. M., Clark, C. T., Jeong, S., & Cervenec, J. (2024). Using Content Area Reading to Support an Interdisciplinary Storyline Involving Climate Science. *Journal of Chemical Education*, 101(9), 3823–3831. <https://doi.org/10.1021/acs.jchemed.4c00390>
- Crocco, F., Wu, Y., Fiser, G., Arabie, C., & Leonard, A. (2026). Engaging Online Learners with H5P: A Study of Student Experiences and Outcomes. *Journal of Interactive Learning Research*, 37, 5–36. <https://doi.org/10.70725/204743ddlhz>
- Deno, M. V. (2025). Systematic Review: Pemanfaatan Media Digital Untuk Inovasi E-Modul Pendidikan. *Jurnal Pelayanan Masyarakat*, 2(4), 138–149. <https://doi.org/10.62951/jpm.v2i4.2607>
- Edison, A. (2025). Design Thinking–mediated Joyful Learning Through AI-interactive Media: An Applied Study on Enhancing Higher-Order Thinking Skills in Secondary Education. *Journal of Advanced Sciences and Mathematics Education*, 5(2), 515–525. <https://doi.org/10.58524/jasme.v5i2.779>
- Fadillah, R., Ganefri, Yulastri, A., & Hidayat, H. (2023). Development of Mobile Learning Based on Digital Entrepreneurs Using Raspberry Pi on TVET. *International Journal on Advanced Science, Engineering and Information Technology*, 13(6), 2231–2239. <https://doi.org/10.18517/ijaseit.13.6.18608>
- Garrison, M. E. B., Daniel, A., Wiersma-Mosley, J. D., Williams, C., Crosswhite, M. R., & Caldwell, I. (2022). 71 Infusing Animal Science Curricula With Cultural Intelligence. *Journal of Animal Science*, 100(Supplement\_1), 45–46. <https://doi.org/10.1093/jas/skac028.085>
- Ginting, F. W., Widya, W., Sakdiah, H., Novita, N., Sulastri, S., & Damanik, A. K. (2024). Interactive Audio-Visual Learning Media Through Articulate Storylines Containing Problem-Based Contextual Learning to Improve Students' HOTS and Scientific Attitudes. *International Journal of Religion*, 5(12), 1031–1044. <https://doi.org/10.61707/z5c4xg78>
- Guo, Q., Zhen, J., Wu, F., He, Y., & Qiao, C. (2025). Can Students Make STEM Progress With the Large Language Models (LLMs)? An Empirical Study of LLMs Integration Within Middle School Science and Engineering Practice. *Journal of Educational Computing Research*, 63(2), 372–405. <https://doi.org/10.1177/07356331241312365>
- Hao, H., & Chen, W. (2026). Research on the Application Effect of BOPPPS and ChatGPT-Based AI-Assisted Teaching in the Machine Learning Course. *The Asia-Pacific Education Researcher*, 35(2), 291–302. <https://doi.org/10.1007/s40299-025-01026-5>
- Hidayati, D., Widiati, U., Zen, E., & Ivone, F. (2025). Developing an LMS-based of ESP course for Islamic undergraduate students. *Social Sciences & Humanities Open*, 11, 101635. <https://doi.org/10.1016/j.ssaho.2025.101635>
- Ho, T. E. (2025). Outcomes of an Integrated STEM With Design Thinking Module on Preschoolers' Science Process Skills. *Journal of Early Childhood Research*, 23(3), 353–368. <https://doi.org/10.1177/1476718x251325675>
- Hu, X., Fang, Y., & Liang, Y. (2024). Roles and Effect of Digital Technology on Young Children's STEM Education: A Scoping Review of Empirical Studies. *Education Sciences*, 14(4), 357. <https://doi.org/10.3390/educsci14040357>
- Huang, C.-H., Hsieh, C.-Y., Chen, Y.-L., & Wedekind, H. (2025). Integrating a Drama-Based Framework with Science Education to Enhance Pre-Service Teachers' Engagement and

- Self-Efficacy: A Cluster-Based Study. *Sage Open*, 15(4), 21582440251384891. <https://doi.org/10.1177/21582440251384891>
- Huang, Y., Wang, W., Lee, H., Lin, C., & Wu, T. (2024). Empowering Virtual Reality With Feedback and Reflection in Hands-on Learning: Effect of Learning Engagement and higher-order Thinking. *Journal of Computer Assisted Learning*, 40(4), 1413–1427. <https://doi.org/10.1111/jcal.12959>
- Ilma, A. Z. ., Wilujeng, I. ., & Prasetyo, Z. K. . (2022). Literature Review of Science Learning Activities with Integrated STEM Education. *Nusantara Science and Technology Proceedings*, 2022(25), 8-14. <https://doi.org/10.11594/nstp.2022.2502>
- Lee, H., Wu, T., Lin, C., Wang, W., & Huang, Y. (2023). Integrating Computational Thinking Into Scaffolding Learning: An Innovative Approach to Enhance Science, Technology, Engineering, and Mathematics Hands-on Learning. *Journal of Educational Computing Research*, 62(2), 211–247. <https://doi.org/10.1177/07356331231211916>
- Li, C. (2025). *Information Literacy And problem-Solving Ability in Chinese College students: The Chain Mediating effects of Learning Engagement and Critical Thinking. PREPRINT (Version 1)*. <https://doi.org/10.21203/rs.3.rs-8308301/v1>
- Ma, B., Lu, M., Taniguchi, Y., & Konomi, S. (2022). Exploring jump back behavior patterns and reasons in e-book system. *Smart Learning Environments*, 9(1), 2. <https://doi.org/10.1186/s40561-021-00183-6>
- Ma, N., Zhang, Y.-L., Liu, C.-P., & Du, L. (2024). The comparison of two automated feedback approaches based on automated analysis of the online asynchronous interaction: A case of massive online teacher training. *Interactive Learning Environments*, 32(7), 3818–3839. <https://doi.org/10.1080/10494820.2023.2191252>
- Manolov, M. (2025). *AI-supported counselor training for socio-ecological resilience*. 17(2), 217–223. <https://doi.org/10.69085/eb20252217>
- Mohammadi, M., Paasivara, M., & Kasurinen, J. (2025). Blended learning in higher education: Good practices in platforms and teachers support, enhancing students motivation. *Education and Information Technologies*, 30(18), 26001–26024. <https://doi.org/10.1007/s10639-025-13770-8>
- Mohseni, Z. (. , Masiello, I., & Martins, R. M. (2023). Co-Developing an Easy-to-Use Learning Analytics Dashboard for Teachers in Primary/Secondary Education: A Human-Centered Design Approach. *Education Sciences*, 13(12), 1190. <https://doi.org/10.3390/educsci13121190>
- Mustapha, M. Z., & Abdullah, N. (2024). The Effects of Flipped Classroom Teaching Method on Science Students' Higher Order Thinking Skills, Engagement and Satisfaction. *International Journal of Research and Innovation in Social Science*, VIII(IIS), 3389–3403. <https://doi.org/10.47772/ijriss.2024.803245s>
- Nasution, H. A. (2025). Implementation of a Higher Order Thinking Skills (HOTS)-Based Chemistry Module With a Science, Technology, Engineering, and Mathematics (STEM) Approach on Thermochemistry Material. *Jurnal Riset Ilmu Pendidikan*, 5(2), 285–289. <https://doi.org/10.56495/jrip.v5i2.927>
- Neyem, A., Cadile, M., Burgos-Martínez, S. A., Alvarado, M. S., Cabello, E. F., Inzunza, O., Tubbs, R. S., & Ottone, N. E. (2026). Integrating Virtual Reality Game-Based Learning to Enhance Metacognition in Medical Anatomy Education. *Clinical Anatomy*, 39(2), 180–206. <https://doi.org/10.1002/ca.70019>
- Nor, N. M., & Halim, L. (2023). Science Teaching and Learning Through Digital Education: A Systematic Literature Review. *International Journal of Academic Research in Progressive Education and Development*. 12(3), 1956-1975. <https://doi.org/10.6007/ijarped/v12-i3/19307>
- Nungu, L., Mukama, E., & Nsabayeze, E. (2023). Online collaborative learning and cognitive presence in mathematics and science education. Case study of university of Rwanda,

- college of education. *Education and Information Technologies*, 28(9), 10865–10884. <https://doi.org/10.1007/s10639-023-11607-w>
- Obaje, N. G., Angwal, Y. A., Mustapha, M. T., Sarangapani, P. M., Maniar, V., Ramchard, M., Kawu, A. A., Adelabu, A. S., Aliyu-Paiko, M., Musa, D. A., Majiya, H., Zakariyya, A., Ewugi, M. S., & Ibrahim, S. (2023). Piloting an Innovation for Teachers' Capacity Development in STEM Subjects in Nigerian Secondary Schools. *GSC Advanced Research and Reviews*, 17(2), 209–220. <https://doi.org/10.30574/gscarr.2023.17.2.0427>
- Okwara, V. U., & Pretorius, J. P. H. (2023). The STEAM vs STEM Educational Approach: The Significance of the Application of the Arts in Science Teaching for Learners' Attitudes Change. *Journal of Culture and Values in Education*, 6(2), 18–33. <https://doi.org/10.46303/jcve.2023.6>
- Porter Rachel, Barnett Jacqueline, Blazar Melinda, Pinheiro Sandro, & Bowlby Lynn. (n.d.). Addressing the Opioid Crisis: A Dynamic Case-Based Module Set for Interprofessional Educators, Learners, and Clinicians. *MedEdPORTAL*, 18, 11238. [https://doi.org/10.15766/mep\\_2374-8265.11238](https://doi.org/10.15766/mep_2374-8265.11238)
- Rahadiani, P., Kekalih, A., Soemantri, D., & Krisnamurti, D. G. B. (2024). Exploring HTML5 Package Interactive Content in Supporting Learning Through Self-Paced Massive Open Online Courses on Healthy Aging: Mixed Methods Study. *JMIR Med Educ*, 10, e45468. <https://doi.org/10.2196/45468>
- Rzyankina, E., George, F., & Simpson, Z. (2024). Enhancing Conceptual Understanding in Engineering Mathematics Through E-Textbooks. *IEEE Transactions on Education*, 67(4), 534–541. <https://doi.org/10.1109/TE.2024.3387102>
- Sariyatun Sariyatun, Leo Sutimin, & Nur Abidin. (2025). Enhancing Historical Thinking and HOTS through Digital Learning Materials: An Inquiry-Based Approach Using Primary Sources for High School Students. *Journal of Curriculum Studies Research*, 7(2). <https://doi.org/10.46303/jcsr.2025.19>
- Shamonia, V., & Semenikhina, O. (2025). STEM Education Landscapes: A Comparative Bibliometric and Pedagogical Overview of Canada and Ukraine (pp. 12–46). open science initiative. <https://doi.org/10.31110/stem-cauk-1.1>
- Skurat Harris, H., & Greer, M. (2022). *Using Multimedia for Instructor Presence in Purposeful Pedagogy-Driven Online Technical Writing Courses*. <https://doi.org/10.1177/0047281620978360>
- Skurat Harris, H., & Greer, M. (2022). Using Multimedia for Instructor Presence in Purposeful Pedagogy-Driven Online Technical Writing Courses. *Journal of Technical Writing and Communication*, 52(1), 110–131. <https://doi.org/10.1177/0047281620978360>
- Smagulov, M., Yesdaulet, Y., & Adilova, S. (2025). *Developing future specialists' competencies through a digital reflective learning model at the university*. <https://doi.org/10.51847/Jv6ekmRXsz>
- Smagulov, M., Yesdaulet, Y., & Adilova, S. (2025). Developing future specialists' competencies through a digital reflective learning model at the university. *Journal of Advanced Pharmacy Education and Research*, 15(4), 142–148. <https://doi.org/10.51847/Jv6ekmRXsz>
- Sofyan, D. N., Herpratiwi, H., Firdaus, R., & Nurwahidin, M. (2025). Implementation of E-Module Flip PDF Higher Order Thinking Skills to Improve Geography Learning Outcomes at Senior High School Level. *Jurnal Teknologi Pendidikan Jurnal Penelitian Dan Pengembangan Pembelajaran*, 10(1), 182. <https://doi.org/10.33394/jtp.v10i1.14168>
- Sutarto, S., Indrawati, I., & Wicaksono, I. (2023). STEM-CP Modul Based Science to Improve Student Independence and Learning Outcomes in Junior High School Science Learning. *Journal of Education Society and Behavioural Science*, 36(7), 106–113. <https://doi.org/10.9734/jesbs/2023/v36i71241>

- Syahfutra, W., Daud, W.A.W., & Hafezah, N. (2024). Application of Fuzzy Delphi Method in the Design of Reading Digital Module for University Students in Riau. *Arab World English Journal*, 15(3): 67-88. <https://dx.doi.org/10.24093/awej/vol15no3.5>
- Utha, K., & Pem, U. (2025). The Impact of the OER Module 'Force and Motion' on Physics Teachers' Knowledge and Practices. *Educational Innovation and Practice*, 10(01), 48–64. <https://doi.org/10.17102/eip.10.2025.03>
- Varma, P., Chheda, K., Goyal, W., & Agarwal, T. (2023). *Digital learning in physiotherapy education: Exploring design approaches through meta-analysis*. 6(2023ss045). <https://doi.org/10.31893/multirev.2023ss045>
- Veselinović, L., Činjarević, M., Turulja, L., & Torlaković, A. (2025). *Let's climb the ladders of digital game-based learning experience: A means-end chain perspective*. <https://doi.org/10.1108/ITSE-09-2024-0210>
- Veselinovic L, Cinjarevic M, Turulja L, Torlakovic A (2025), "Let's climb the ladders of digital game-based learning experience: a means-end chain perspective". *Interactive Technology and Smart Education*, 22(4), 699–722.
- Vilppola, J., Lämsä, J., Vähäsantanen, K., & Hämäläinen, R. (2022). Teacher Trainees' Experiences of the Components of ICT Competencies and Key Factors in ICT Competence Development in Work-Based Vocational Teacher Training in Finland. *International Journal for Research in Vocational Education and Training*, 9(2), 146–166. <https://doi.org/10.13152/IJRVET.9.2.1>
- Wang, X.-M., Wang, J.-L., Xu, S.-Y., & Xu, S.-J. (2025). Concept mapping in STEM education: A meta-analysis of its impact on students' achievement (2004–2023). *International Journal of STEM Education*, 12(1), 30. <https://doi.org/10.1186/s40594-025-00554-2>
- Xu, S.-R., & Zhou, S. (2022). The Effect of Students' Attitude Towards Science, Technology, Engineering, and Mathematics on 21st Century Learning Skills: A Structural Equation Model. *Journal of Baltic Science Education*, 21(4), 706–719. <https://doi.org/10.33225/jbse/22.21.706>
- Yang, W., & Chen, L. (2024). Research on the Theoretical Framework and Practical Countermeasures of Junior Middle School Mathematics Interdisciplinary Study Based on STEM. *SHS Web of Conferences*, 187, 01009. <https://doi.org/10.1051/shsconf/202418701009>
- Yoon, J., Lee, H., & Mun, J. (2025). Cultural STEM Night: An Online Collaboration for Culturally Responsive Teaching Between American and Korean Teacher Candidates. *Education Sciences*, 15(8), 1084. <https://doi.org/10.3390/educsci15081084>
- Zhou, S., & Bakhir, N. M. (2024). Interdisciplinary Art Learning Through Artistic Digital Game-Based Learning (DGBL): Evaluating Learning Outcomes and Processes Among Science and Engineering Students. *Empirical Studies of the Arts*, 43(1), 584–617. <https://doi.org/10.1177/02762374241246948>
- Zhou, Y., Liu, W., Wu, Y., Apaeva, S., & Ibraimova, B. (2025). An innovative Application of Integrating Transmedia Storytelling and Digital Technologies into Local Culture in China. *International Journal on Culture, History, and Religion*, 7, 915–940. <https://doi.org/10.63931/ijchr.v7iSI1.351>