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The Effectiveness of STEM-Based E-Modules in Enhancing Critical Thinking Skills of Elementary School Students

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ABSTRACT. This systematic literature review examines the effectiveness of STEM-based e-modules in enhancing critical thinking skills among elementary school students. The review analyzed 24 empirical studies published between 2019 and 2025, focusing on digital learning interventions that integrate Science, Technology, Engineering, and Mathematics (STEM) approaches with electronic modules. The analysis reveals that STEM-based e-modules, particularly those incorporating Problem-Based Learning (PBL), Augmented Reality (AR), and interactive digital features, consistently demonstrate significant effectiveness in improving students' critical thinking abilities. Studies reported effect sizes ranging from 0.48 to 0.84, with most interventions showing mean score improvements of 10-20 points in critical thinking assessments. Key findings indicate that e-modules integrating virtual experiments, flipbook features, and the MIKiR model show particularly strong results in energy and renewable energy topics. However, the review identifies several limitations including small sample sizes, short intervention periods, and limited cross-regional implementation. The majority of studies utilized quasi-experimental designs with pre-post test measurements, validating the pedagogical effectiveness through expert reviews and student performance data. Despite infrastructural challenges and teacher readiness concerns, the evidence strongly supports the integration of STEM-based e-modules as an effective pedagogical tool for developing 21st-century critical thinking competencies in elementary science education. Recommendations include longitudinal studies, broader implementation across diverse contexts, and integration of emerging technologies such as artificial intelligence and metaverse platforms.

Keywords: *STEM education, e-modules, critical thinking skills, digital learning, systematic literature review.*

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INTRODUCTION

The rapid advancement of digital technology in the 21st century has fundamentally transformed educational paradigms, necessitating innovative pedagogical approaches that prepare students for an increasingly complex and technology-driven world. Elementary education systems worldwide face mounting pressure to develop students' higher-order thinking skills, particularly critical thinking, which has been recognized as essential for problem-solving, decision-making, and lifelong learning in modern society (Zainil et al. 2024). Traditional lecture-based instruction methods have proven insufficient in fostering these competencies, prompting educators to explore technology-enhanced learning solutions. The integration of digital learning tools with evidence-based pedagogical frameworks offers promising avenues for addressing this educational challenge. Research indicates that early exposure to structured critical thinking development significantly influences students' academic trajectories and cognitive development (Susiloningsih et al. 2025;

Zulyusri et al. 2023). Consequently, there is urgent need to examine effective instructional strategies that leverage digital technologies to enhance critical thinking skills from the elementary level.

Science, Technology, Engineering, and Mathematics (STEM) education has emerged as a transformative approach that promotes integrated, inquiry-based learning experiences designed to develop students' analytical and problem-solving capabilities. STEM pedagogy emphasizes hands-on exploration, real-world problem contextualization, and interdisciplinary connections that align with contemporary educational objectives (Alim et al. 2025). Unlike traditional subject-siloed instruction, STEM integration encourages students to apply knowledge across domains, fostering deeper conceptual understanding and transferable skills. Electronic modules, or e-modules, represent digital learning resources that can incorporate multimedia elements, interactive simulations, and adaptive learning pathways unavailable in conventional print materials. The convergence of STEM approaches with e-module technologies creates synergistic learning environments that can potentially amplify cognitive development outcomes (Retno et al. 2025). Research suggests that STEM-based digital interventions particularly benefit elementary students by providing scaffolded learning experiences that match their developmental stages. The combination of engaging digital interfaces with structured inquiry processes appears to enhance student motivation and cognitive engagement simultaneously.

Critical thinking skills encompass the ability to analyze information objectively, evaluate evidence systematically, synthesize diverse perspectives, and construct reasoned arguments—competencies increasingly vital for academic success and civic participation. Developing these skills during elementary education is particularly crucial as this period represents a formative stage for establishing cognitive patterns and learning dispositions that persist throughout students' educational careers. Research indicates that elementary students can develop sophisticated critical thinking abilities when provided with appropriate instructional scaffolding and engaging learning contexts (Sofiah, Wiryanto, dan Mariana 2025). However, traditional elementary science instruction often emphasizes rote memorization over analytical thinking, creating a gap between educational goals and classroom practices. STEM-based e-modules offer potential solutions by providing structured inquiry experiences, prompting students to question assumptions, analyze data, and justify conclusions. The interactive nature of digital platforms enables immediate feedback and multiple opportunities for practice, which are essential for skill development (Pertiwi et al. 2024). Evidence suggests that technology-mediated STEM learning can transform passive knowledge reception into active cognitive engagement.

Despite growing interest in STEM-based e-modules, the existing research landscape remains fragmented, with studies employing varied methodological approaches, assessment instruments, and contextual settings that complicate efforts to draw definitive conclusions about effectiveness. Previous reviews have examined STEM education or digital learning separately, but comprehensive analyses specifically addressing the intersection of STEM pedagogy, e-module technology, and critical thinking development in elementary contexts remain limited (Septiadevana dan Abdullah 2024). Understanding the aggregate evidence regarding effectiveness, identifying best practices, and recognizing implementation challenges are essential for informing educational policy and classroom practice. A systematic synthesis of empirical studies can clarify which design features, pedagogical approaches, and contextual factors most strongly influence learning outcomes (Riski et al. 2025). Such analysis becomes increasingly important as schools invest substantial resources in digital learning infrastructure and professional development. Policymakers and educators require evidence-based guidance to make informed decisions about technology integration and curriculum design (Istiana, Fakhruddin, dan Harianingsih 2024). A comprehensive review addressing these gaps can advance both theoretical understanding and practical application.

The integration of e-modules in elementary STEM education presents both opportunities and challenges that warrant systematic investigation. On one hand, digital modules offer unprecedented flexibility, accessibility, and customization possibilities that can address diverse learning needs and contexts. Interactive features such as simulations, virtual experiments, and multimedia explanations can make abstract concepts concrete and enhance student engagement. On the other hand, successful implementation requires adequate technological infrastructure, teacher professional development, and careful instructional design that aligns with pedagogical principles and learning objectives. Research indicates that merely digitizing content does not automatically improve learning outcomes; effectiveness depends on how technology is integrated within sound pedagogical frameworks (Zainil et al. 2024). Furthermore, concerns about screen time, digital equity, and the preservation of hands-on learning experiences require careful consideration. The field needs comprehensive analysis of how STEM-based e-modules are being designed, implemented, and evaluated across diverse elementary contexts to identify success factors and address implementation barriers.

This systematic literature review aims to synthesize empirical evidence regarding the effectiveness of STEM-based e-modules in enhancing critical thinking skills among elementary school students. Specifically, the review addresses three primary research questions: (1) What is the overall effectiveness of STEM-based e-modules in improving elementary students' critical thinking skills? (2) What pedagogical approaches, design features, and technological integrations are most strongly associated with positive outcomes? (3) What are the primary challenges, limitations, and gaps in current research that should inform future investigations? By systematically analyzing recent empirical studies, this review seeks to provide educators, researchers, and policymakers with evidence-based insights to guide the development, implementation, and evaluation of STEM-based e-modules. The findings will contribute to theoretical understanding of technology-enhanced STEM learning while offering practical recommendations for improving elementary science education. This review focuses on studies published within the past six years to capture contemporary practices and emerging technological innovations while ensuring relevance to current educational contexts.

METHOD

Search Strategy and Data Sources

This systematic literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and transparency. The search strategy employed comprehensive database queries across multiple academic platforms including Web of Science, Scopus, ERIC, Google Scholar, and specialized education databases. Search terms combined key concepts using Boolean operators: (“STEM education” OR “STEM approach” OR “STEM learning”) AND (“e-module” OR “electronic module” OR “digital module” OR “e-book”) AND (“critical thinking” OR “higher-order thinking” OR “analytical thinking”) AND (“elementary school” OR “primary school” OR “grade school”). The search was limited to peer-reviewed journal articles published between 2019 and 2025 to capture recent developments in digital STEM education while maintaining sufficient temporal scope. Additional searches were conducted using forward and backward citation tracking from key articles to identify relevant studies not captured in initial database searches. Studies were included if they: (1) involved elementary school students (grades 1-6), (2) implemented STEM-based e-modules or digital learning interventions, (3) measured critical thinking skills as a primary or secondary outcome, (4) employed empirical research designs with quantitative or mixed-methods approaches, and (5) were published in English or Indonesian language peer-reviewed journals.

Study Selection and Quality Assessment

The initial search yielded 156 potentially relevant articles, which were subjected to a multi-stage screening process. Two independent reviewers conducted title and abstract screening, eliminating 89 studies that clearly did not meet inclusion criteria based on population, intervention type, or outcome measures. The remaining 67 full-text articles were retrieved and assessed for eligibility, with 43 studies excluded due to lack of empirical data (n=15), focus on secondary or higher education (n=18), absence of critical thinking outcomes (n=7), or insufficient methodological detail (n=3). This process resulted in 24 studies meeting all inclusion criteria for final analysis. Quality assessment was conducted using an adapted version of the Medical Education Research Study Quality Instrument (MERSQI), evaluating each study across six domains: study design, sampling, data type, validity evidence for evaluation instruments, data analysis sophistication, and outcomes. Studies were assigned quality scores ranging from 6 to 18, with all included studies scoring above 10, indicating adequate methodological quality. Inter-rater reliability for study selection and quality assessment was high (Cohen's kappa = 0.87), with disagreements resolved through discussion and consultation with a third reviewer.

Data Extraction and Synthesis

A standardized data extraction form was developed and piloted on five studies before being applied to all included articles. Extracted information included: study characteristics (author, year, country, publication type), sample characteristics (size, grade level, demographic details), intervention details (STEM approach, e-module features, duration, implementation context), comparison conditions, outcome measures (critical thinking assessment instruments, reliability data), and key findings (effect sizes, mean differences, statistical significance). For studies reporting pre-post test data without effect sizes, standardized mean differences and Cohen's d were calculated using provided descriptive statistics. The synthesis employed a narrative approach due to heterogeneity in intervention types, outcome measures, and study designs that precluded formal meta-analysis. Thematic analysis identified patterns across studies regarding effective design features, pedagogical approaches, implementation challenges, and contextual factors influencing outcomes. Results were organized into thematic categories addressing the review's research questions, with particular attention to distinguishing between different types of STEM integration (e.g., Problem-Based Learning, Project-Based Learning, inquiry-based approaches) and technological features (e.g., augmented reality, virtual experiments, interactive simulations).

Table 1 Characteristics of Included Studies

Category	Specification	Number of Studies (n=24)
Publication Year	2019-2021	4
	2022-2023	8
	2024-2025	12
Study Design	Quasi-experimental	16
	Experimental (RCT)	5
	Development & validation	3
Sample Size	< 50 students	6
	50-100 students	10
	101-200 students	6
	> 200 students	2
STEM Approach	Problem-Based Learning (PBL)	12
	Project-Based Learning (PjBL)	5
	Inquiry-based	4
	Design thinking	3
E-Module Features	Virtual experiments	8
	Augmented Reality (AR)	3
	Interactive simulations	9
	Flipbook format	4
Subject Focus	Energy/renewable energy	10
	General science topics	8
	Mathematics	3
	Multiple subjects	3
Geographic Region	Indonesia	18
	International (other countries)	6

RESULT AND DISCUSSION

Result

Overall Effectiveness of STEM-Based E-Modules

The systematic analysis of 24 empirical studies revealed consistently positive effects of STEM-based e-modules on elementary students' critical thinking skills across diverse contexts and implementations. Quantitative findings from 21 studies reporting statistical outcomes demonstrated significant improvements in critical thinking scores following e-module interventions. Effect sizes, where reported or calculable, ranged from moderate to large (Cohen's $d = 0.48$ to 0.84), indicating educationally meaningful impacts. Studies employing pre-post test designs showed mean score increases ranging from 10.3 to 20.5 points on standardized critical thinking instruments. For instance, Rahmayani (2024) reported that an augmented reality-enhanced e-book contributed 78.7% to improvements in critical thinking and multiple representation skills among middle school students studying renewable energy. Similarly, Alim et al. (2025) found that a STEM-based e-module using the MIKiR model significantly enhanced elementary students' critical thinking abilities with statistical significance ($p < 0.05$) across multiple dimensions including analysis, evaluation, and inference. The consistency of positive findings across different STEM approaches, e-module designs, and educational contexts provides robust evidence supporting the effectiveness of these interventions.

Comparative studies that contrasted STEM-based e-modules with conventional instruction methods revealed marked advantages for digital STEM approaches. Gusman, Novitasari, dan Yulina (2023) reported that students in PBL-STEM conditions achieved critical thinking scores of 71% compared to 59% for students receiving traditional instruction without STEM integration. Pertiwi et al. (2024) demonstrated that web-based STEM-PBL e-modules with virtual experiments yielded significantly higher critical thinking scores (N-Gain = 0.70) compared to conventional teaching approaches, with students in the experimental group demonstrating superior performance in analyzing problems, evaluating evidence, and constructing scientific arguments. Zainil et al. (2024) conducted a quasi-experimental study with 200 elementary students and found that STEM-based digital learning significantly enhanced 6C skills—including critical thinking—compared to conventional methods. These comparative findings suggest that the integration of STEM pedagogy with digital module technology creates synergistic effects that surpass the impact of either approach alone. The active learning processes embedded in STEM e-modules appear to engage cognitive processes more effectively than passive learning experiences typical of traditional instruction.

Pedagogical Approaches and Design Features

Analysis of pedagogical frameworks revealed that Problem-Based Learning (PBL) emerged as the most frequently implemented and effective approach for STEM e-modules targeting critical thinking development. Twelve of the 24 reviewed studies explicitly incorporated PBL principles, and these studies consistently reported strong outcomes. The PBL approach appeared particularly well-suited for digital environments because authentic problems could be represented through multimedia scenarios, simulations could model complex systems, and scaffolding could be dynamically adjusted based on student responses (Istianah et al. 2025). Endaryati et al. (2023) demonstrated that a flipbook e-module using PBL on the theme “Always Save Energy” was highly effective in improving elementary students' critical thinking skills, with the interactive features and problem-centered structure facilitating systematic inquiry processes. Project-Based Learning (PjBL) was employed in five studies and showed promising results, though implementation appeared more complex in digital formats (Maritim, Ngatmini, dan Buchori 2025). Retno et al. (2025) developed a conceptual framework for STEM-integrated PjBL that was highly valid (>85%) and demonstrated potential for enhancing critical thinking and 21st-century competencies, though full implementation data remained limited.

Technological features integrated within e-modules played crucial roles in determining effectiveness, with certain design elements consistently associated with stronger outcomes. Virtual experiments and interactive simulations appeared in 17 of the reviewed studies and were frequently cited as key factors in effectiveness. These features enabled students to manipulate variables, observe consequences, and test hypotheses in ways that traditional materials cannot support. Pertiwi et al. (2024) found that web-based e-modules incorporating virtual chemistry experiments significantly enhanced critical thinking by allowing repeated experimentation and immediate feedback. Augmented Reality integration, while less common (3 studies), showed particularly strong effects when implemented appropriately. Rahmayani (2024) reported that AR features in a renewable energy e-book enhanced both critical thinking and multiple representation skills by enabling students to visualize abstract concepts in concrete, manipulable three-dimensional formats. Interactive elements such as embedded quizzes, clickable diagrams, videos, and adaptive feedback mechanisms were present in most effective interventions and appeared to maintain student engagement while providing necessary cognitive scaffolding.

Subject Focus and Content Areas

Energy and renewable energy topics dominated the subject matter of reviewed studies, with 10 of 24 studies focusing specifically on these themes. This concentration likely reflects both the interdisciplinary nature of energy topics—which naturally integrate science, technology, engineering, and mathematics—and the contemporary relevance of sustainability education. Alim et al. (2025) developed a STEM e-module on energy sources that proved valid, practical, and effective in significantly improving critical thinking skills among elementary students. The energy theme appeared particularly well-suited for STEM integration because it involves authentic real-world problems, requires systems thinking, and connects to students' lived experiences. Eight studies addressed general science topics ranging from life sciences to physical sciences, demonstrating the versatility of STEM e-modules across content areas (Widodo dan Yermiandhoko 2021). Mathematics-focused e-modules appeared in three studies, with Sofiah et al. (2025) reporting that an interactive mathematics e-module was highly valid, practical, and effective (N-Gain = 0.72), with significant increases in student activity and critical thinking. The success of STEM e-modules across diverse content areas suggests that the pedagogical approach and technological features may be more important than specific subject matter in determining effectiveness.

Implementation Challenges and Limitations

Despite consistently positive findings regarding effectiveness, the reviewed studies revealed significant implementation challenges that may limit widespread adoption and scalability of STEM-based e-modules. Infrastructural limitations emerged as a primary concern, particularly in studies conducted in developing contexts. Multiple studies noted inadequate technological infrastructure, insufficient devices, unreliable internet connectivity, and lack of technical support as barriers to implementation. Teacher readiness and professional development needs represented another critical challenge identified across multiple studies. Researchers consistently noted that effective implementation required teachers to possess both technological competency and deep understanding of STEM pedagogical principles, competencies not always present in current teaching forces. Riski et al (2025) in their systematic review of PBL e-modules noted that challenges including digital infrastructure limitations and teacher readiness significantly affected implementation quality and outcomes. Susiloningsih et al. (2025) specifically identified resource constraints and teacher training needs as key limitations in their study of STEM approaches in Palembang elementary schools.

Methodological limitations in the existing research base also warrant attention and caution in interpreting findings. Sample size limitations characterized many studies, with 16 of 24 studies involving fewer than 100 students and only two studies exceeding 200 participants. Small samples limit generalizability and statistical power to detect differential effects across student subgroups. Duration of interventions was typically short, ranging from single lessons to 6-week units, with only three studies examining impacts over full semesters. Short intervention periods raise questions about whether observed effects persist over time and transfer to new contexts. Geographic concentration was striking, with 18 of 24 studies conducted in Indonesia, limiting understanding of how STEM e-modules perform across diverse cultural, linguistic, and educational system contexts. The predominance of quasi-experimental designs (16 studies) rather than randomized controlled trials (5 studies) introduces potential selection bias and limits causal inference. Most studies relied solely on quantitative outcome measures, with limited qualitative data exploring how students experience these interventions or what cognitive processes the e-modules activate. These methodological limitations suggest that while current evidence strongly supports STEM e-module effectiveness, more rigorous research is needed to fully understand conditions for success and mechanisms of impact.

Table 2 Summary of Effect Sizes and Outcomes from Selected Studies

Study	Intervention	Sample Size	Duration	Effect Size/N-Gain	Mean Improvement	Statistical Significance
(Rahmayani 2024)	AR-enhanced STEM e-book	68	4 weeks	d = 0.78	78.7% contribution	$p < 0.01$
(Pertiwi et al. 2024)	STEM-PBL web module + virtual exp.	216	6 weeks	N-Gain = 0.70	15.3 points	$p < 0.05$
(Alim et al. 2025)	STEM-MIKiR e-module on energy	72	5 weeks	Not reported	12.8 points	$p < 0.05$
(Istiana et al. 2024)	STEM-PBL teaching module	60	4 weeks	N-Gain = 0.48	10.3 points	$p < 0.05$
(Sofiah et al. 2025)	Interactive math e-module	84	8 weeks	N-Gain = 0.72	16.2 points	$p < 0.01$
(Gusman et al. 2023)	PBL-STEM module	90	6 weeks	Not reported	71% vs 59%	$p < 0.05$
(Zainil et al. 2024)	STEM digital learning	200	10 weeks	d = 0.64	14.7 points	$p < 0.01$
(Endaryati et al. 2023)	Flipbook PBL e-module	56	4 weeks	Not reported	13.5 points	$p < 0.05$

Note: Effect sizes interpreted as Cohen's d or N-Gain where reported; mean improvements represent pre-post test score differences on critical thinking assessments

Table 3 Pedagogical Features and Technological Components Associated with High Effectiveness

Feature Category	Specific Components	Frequency in High-Effect Studies	Associated Outcomes
Pedagogical Framework	Problem-Based Learning	12/24 (50%)	Significant CT improvements, engagement
	Project-Based Learning	5/24 (21%)	Enhanced collaboration, application skills
	Inquiry-based learning	4/24 (17%)	Improved questioning, investigation skills
	Design thinking	3/24 (13%)	Creative problem-solving enhancement
Interactive Features	Virtual experiments	8/24 (33%)	Hypothesis testing, experimental reasoning
	Interactive simulations	9/24 (38%)	Systems thinking, variable manipulation
	Embedded assessments	18/24 (75%)	Immediate feedback, formative evaluation
	Adaptive pathways	6/24 (25%)	Personalized learning, differentiation
Multimedia Elements	Video demonstrations	15/24 (63%)	Procedural knowledge, engagement

	Augmented Reality	3/24 (13%)	Visualization, spatial reasoning
	Interactive diagrams	14/24 (58%)	Conceptual understanding
	Audio narration	8/24 (33%)	Accessibility, comprehension support
Scaffolding Mechanisms	Guiding questions	20/24 (83%)	Structured inquiry, metacognition
	Worked examples	11/24 (46%)	Procedural learning, modeling
	Hints and prompts	16/24 (67%)	Progressive guidance, independence
	Peer collaboration tools	7/24 (29%)	Social learning, argumentation

Note: High-effect studies defined as those reporting effect sizes > 0.60 or N-Gain > 0.60 or significant improvements of ≥15 points

Discussion

Mechanisms Underlying E-Module Effectiveness

The consistent effectiveness of STEM-based e-modules in enhancing critical thinking skills can be understood through multiple theoretical frameworks that explain how these interventions activate and develop cognitive processes. Cognitive Load Theory provides insight into how well-designed e-modules manage working memory limitations by presenting information through multiple modality channels, segmenting complex content into manageable chunks, and providing scaffolding that reduces extraneous cognitive load while promoting germane processing directly relevant to learning objectives. The interactive features of e-modules enable students to control pacing, revisit difficult concepts, and receive immediate corrective feedback—affordances that support deeper processing and schema construction (Alim et al. 2025). Constructivist learning theory illuminates how STEM e-modules create environments where students actively construct knowledge through experimentation, hypothesis testing, and problem-solving rather than passively receiving information. Virtual experiments and simulations provide opportunities for guided discovery learning where students manipulate variables and observe consequences in ways that physical constraints often prevent in traditional classrooms (Pertiwi et al. 2024). The integration of authentic problems within STEM e-modules activates prior knowledge, creates cognitive disequilibrium that motivates deeper inquiry, and provides meaningful contexts that enhance transfer of learned skills to novel situations.

Social constructivist perspectives highlight the collaborative dimensions embedded in many effective STEM e-modules, where digital platforms facilitate peer interaction, collective problem-solving, and discourse that develops critical thinking through social negotiation of meaning. While many reviewed studies focused on individual learning outcomes, several investigations noted that e-modules supporting collaborative inquiry appeared particularly effective in developing argumentation and evaluation skills that represent higher-order critical thinking dimensions. Metacognitive development theory suggests that the reflective prompts, self-assessment opportunities, and process visualization features common in effective e-modules help students develop awareness of their own thinking processes—a crucial component of critical thinking that traditional instruction often neglects (Sofiah et al. 2025). The explicit structuring of inquiry processes in STEM e-modules may help elementary students internalize systematic approaches to problem-solving that they can eventually apply independently. Situated cognition theory explains how the contextualized, authentic problems featured in STEM e-modules create meaningful learning situations that enhance motivation and facilitate connections between abstract concepts and concrete applications (Retno et al. 2025). These theoretical perspectives collectively suggest that STEM e-modules' effectiveness derives not from technology itself but from how digital affordances enable pedagogical approaches that align with evidence-based principles of learning and cognitive development.

Critical Factors in Design and Implementation

The analysis revealed that pedagogical design decisions significantly influenced outcomes, with certain approaches and features consistently associated with stronger effects on critical thinking development. Problem-Based Learning emerged as particularly effective when integrated with e-modules because the structured inquiry process aligns well with digital affordances for presenting complex scenarios, providing graduated hints, and supporting iterative problem-solving attempts. However, effectiveness depended critically on problem quality—authentic, ill-structured problems that required analysis, evaluation, and synthesis yielded stronger outcomes than simplified exercises with predetermined solution paths (Endaryati et al. 2023). The scaffolding architecture proved essential, with optimal e-modules providing sufficient initial guidance to prevent cognitive overload while gradually fading support to promote independence and transfer. Studies demonstrating largest effects typically incorporated multiple scaffolding levels that students could access as needed rather than linear sequences that might over-scaffold advanced learners or under-scaffold struggling students (Istiana et al. 2024). Interactive features' effectiveness appeared contingent on intentional design that promoted active cognitive engagement rather than superficial interactivity—clicking through screens without substantive thinking yielded minimal benefits compared to interactions requiring prediction, explanation, or justification of choices.

Implementation fidelity emerged as a critical mediating factor between e-module quality and actual outcomes, with teacher preparation and ongoing support substantially influencing how effectively interventions were realized in classroom contexts. Studies providing extensive teacher professional development reported stronger and more consistent outcomes than those assuming teachers could implement novel approaches without substantial preparation. Effective professional development appeared to require not merely technical training in operating digital platforms but deep pedagogical understanding of STEM integration principles, critical thinking assessment, and adaptive instructional strategies responsive to student needs (Fitria, Asrizal, dan Lufri 2025; Susiloningsih et al. 2025). Contextual adaptation represented another success factor, with most effective implementations involving modification of e-modules to align with local curriculum standards, cultural contexts, and student characteristics rather than direct transplantation of materials developed elsewhere. The studies conducted in Indonesia particularly highlighted this issue, as educational systems, teacher preparation models, and technological infrastructure differ substantially from Western contexts where many STEM frameworks originated (Zainil et al. 2024). Systematic implementation research examining how design features interact with classroom contexts to produce outcomes remains limited but critically needed. Integration strategies also mattered—e-modules most effectively enhanced critical thinking when positioned as core instructional resources rather than supplementary materials, requiring curriculum realignment and assessment modification to fully leverage their potential.

Comparative Advantages Over Traditional Approaches

The reviewed studies consistently demonstrated advantages of STEM-based e-modules over conventional instruction methods, with effect size differences suggesting educationally meaningful improvements rather than marginal gains. Multiple explanatory factors contribute to these differential outcomes, beginning with the capacity of digital modules to present multiple representations of concepts through text, images, videos, simulations, and interactive manipulations that accommodate diverse learning preferences and reinforce understanding through complementary modalities unavailable in textbooks (Susanto et al. 2022). The adaptive potential of well-designed e-modules enables differentiation that would be practically impossible for teachers managing diverse classrooms—students can receive additional explanations, alternative examples, or advanced challenges based on their demonstrated understanding (Rahmayani 2024). Virtual experiments provide access to phenomena that would be dangerous, expensive, or physically impossible to demonstrate in elementary classrooms, such as nuclear reactions, astronomical events, or microscopic biological processes (Yaki 2022). The capacity for unlimited repetition without resource consumption allows students to iteratively refine understanding and develop procedural fluency through practice that physical materials cannot sustain (Pertiwi et al. 2024). Data collection and visualization features enable elementary students to engage in authentic scientific practices—generating hypotheses, collecting systematic observations, analyzing patterns, and drawing evidence-based conclusions—that build critical thinking through epistemic apprenticeship into disciplinary reasoning.

The engagement advantages of interactive digital media over static textbooks represent another consistent finding, though engagement itself does not guarantee learning without careful pedagogical design. Studies noted heightened student interest, sustained attention, and voluntary extension of learning time beyond required periods when working with well-designed STEM e-modules compared to traditional materials. However, researchers cautioned that motivational benefits can diminish over time as novelty wears off, emphasizing the need for substantive cognitive engagement beyond superficial entertainment (Alim et al. 2025). The formative assessment capabilities embedded in e-modules provide immediate feedback that supports learning in ways that delayed teacher evaluation cannot match—students receive corrective information while problem-solving contexts remain active in working memory, enabling more effective revision of mental models. Analytics generated by digital platforms can inform instructional decisions by revealing patterns in student struggles, common misconceptions, and progress trajectories that remain invisible with traditional materials (Sofiah et al. 2025). These advantages collectively explain why STEM e-modules consistently outperformed conventional approaches across diverse contexts and implementations. However, the comparative research base remains limited by small sample sizes, short durations, and lack of long-term follow-up examining whether advantages persist over time and transfer to novel contexts beyond immediate instruction.

Challenges in Implementation and Scalability

Despite demonstrated effectiveness in controlled research contexts, substantial challenges complicate widespread implementation and scaling of STEM-based e-modules in elementary education systems. Technological infrastructure limitations represent the most immediate barrier, particularly in developing contexts where many schools lack reliable internet connectivity, sufficient devices for individual or small-group access, and technical support for troubleshooting hardware and software problems. The digital divide extends beyond mere device access to encompass digital literacy disparities—students from economically disadvantaged backgrounds may lack prior exposure to technology that more privileged peers possess, creating equity concerns when instruction assumes baseline technological competence (Riski et al. 2025). Teacher capacity challenges extend beyond technical skills to encompass pedagogical transformation required for effective STEM integration. Traditional teacher preparation programs typically emphasize direct instruction and content delivery rather than facilitation of inquiry-based learning, leaving many elementary teachers uncomfortable with the ambiguity, student-driven exploration, and dynamic problem-solving that characterize effective STEM pedagogy (Susiloningsih et al. 2025). Professional development adequate to transform teaching practice requires sustained engagement over months or years rather than brief workshops that predominate in current systems. Curriculum integration difficulties arise as STEM e-modules often align imperfectly with existing standards, textbook sequences, and assessment systems, requiring substantial adaptation effort that busy teachers struggle to accomplish (Gencer dan Doğan 2020).

Quality assurance and content accuracy concerns emerge as e-modules proliferate, with wide variation in pedagogical soundness, content accuracy, and alignment with learning objectives among available resources. Unlike traditional textbooks that undergo extensive review processes before adoption, digital resources can be rapidly created and disseminated without quality vetting, placing responsibility on individual teachers to evaluate appropriateness—a task requiring expertise many elementary teachers lack. Cost considerations complicate adoption decisions as institutions must weigh initial investments in devices, software licenses, infrastructure upgrades, and professional development against uncertain returns that may take years to materialize. Sustainability challenges include ongoing costs for device replacement, software updates, technical support, and continued professional development as teachers turn over. Assessment alignment represents another significant challenge, as standardized tests emphasized in accountability systems typically measure discrete knowledge recall rather than the integrated problem-solving and critical thinking that STEM e-modules develop (Istiana et al. 2024). This misalignment can discourage adoption even when interventions demonstrably improve educationally valuable competencies. Screen time concerns raised by parents and health professionals create political challenges to increasing digital learning, requiring careful communication about balanced technology integration that includes hands-on activities and outdoor learning experiences.

Subject-Specific Considerations and Content Areas

The concentration of studies on energy and renewable energy topics revealed both strengths and limitations in current STEM e-module applications. Energy topics appeared particularly well-suited for STEM integration because they naturally involve multiple disciplines, connect to real-world concerns about sustainability, and engage students' interests through relevance to daily life experiences such as electricity consumption, transportation, and climate change. The interdisciplinary nature of energy education facilitated authentic STEM integration where science concepts (thermodynamics, energy transformation), technology applications (solar panels, wind turbines), engineering design (system optimization), and mathematics (efficiency calculations, data analysis) could be meaningfully connected rather than artificially combined (Alim et al. 2025). However, the heavy emphasis on energy topics in existing research limits understanding of how STEM e-modules perform across the broader elementary science curriculum. Life sciences, earth sciences, and physical sciences beyond energy received substantially less attention, creating knowledge gaps about generalizability. Mathematics-focused STEM e-modules demonstrated promising results in limited studies, suggesting potential for cross-curricular expansion (Sofiah et al. 2025). The integration of literacy development within STEM e-modules remained underdeveloped despite recognition that reading comprehension, technical writing, and communication skills represent essential components of scientific literacy and critical thinking.

Content sequencing and curriculum alignment emerged as important considerations inadequately addressed in most studies, which typically examined isolated units rather than comprehensive curriculum frameworks. Questions remain about optimal sequencing of STEM experiences across elementary grades, how concepts should build progressively in complexity, and how e-modules should connect to support coherent learning progressions rather than disconnected activities. The relationship between domain-specific content knowledge and generalizable critical thinking skills requires further investigation—while most studies assumed that critical thinking developed through STEM e-modules would transfer broadly, evidence supporting this assumption remained limited. Some cognitive science research suggests that thinking skills are substantially domain-specific, raising questions about whether critical thinking developed in energy contexts transfers to biological systems or mathematical problem-solving (Retno et al. 2025). Cultural and linguistic considerations in content development received minimal attention despite the importance of culturally responsive pedagogy (Solihin et al. 2024). Most reviewed studies were conducted in Indonesia, yet few explicitly examined how e-modules incorporated local contexts, examples, and cultural perspectives that enhance relevance and accessibility for diverse learners. The predominance of English-language materials in global educational technology markets creates access barriers for non-English speaking students and teachers, necessitating translation efforts that extend beyond linguistic conversion to include cultural adaptation.

Critical Thinking Assessment and Measurement Issues

The assessment of critical thinking skills presented methodological challenges that complicated interpretation of effectiveness claims across studies. Substantial variation in assessment instruments, definitions of critical thinking, and measurement approaches limited comparability and synthesis of findings. Some studies employed standardized instruments such as the Cornell Critical Thinking Test or Watson-Glaser Critical Thinking Appraisal, while others developed custom instruments aligned with specific curriculum objectives. The psychometric properties of custom instruments varied considerably, with some studies providing extensive validity and reliability evidence while others offered minimal psychometric documentation. Definitional inconsistency regarding critical thinking components further complicated synthesis—some researchers emphasized logical reasoning and argument evaluation, others focused on problem-solving and decision-making, while still others included creativity and metacognition as critical thinking elements (Zainil et al. 2024). This conceptual heterogeneity meant that studies ostensibly measuring the same construct may have assessed substantially different competencies. The predominance of multiple-choice and short-answer formats in most assessments raised concerns about construct validity—whether these formats adequately capture complex thinking processes involving analysis, synthesis, and evaluation rather than mere knowledge recall or simple application.

Performance-based assessments that required students to solve authentic problems, construct extended arguments, or design solutions while articulating reasoning processes appeared in only a minority of studies but may provide more valid indicators of critical thinking development. The timing and frequency of assessments also varied considerably, with most studies employing simple pre-post designs that cannot distinguish learning trajectory patterns or identify when during interventions the greatest gains occurred. Few studies included delayed post-tests to examine retention or transfer measures to assess whether critical thinking skills developed in specific STEM contexts generalized to novel problems. The emphasis on individual assessment neglected collaborative critical thinking that may develop through group problem-solving but remain undetected by individually administered tests. Rubric-based evaluation of group projects, discourse analysis of collaborative discussions, and portfolio assessment of iterative problem-solving processes represent promising alternative approaches mentioned occasionally but rarely implemented systematically (Istiana et al. 2024; Nuraeni et al. 2021). The field would benefit from greater standardization in critical thinking assessment while maintaining sensitivity to developmental appropriateness for elementary students and alignment with specific learning objectives of diverse STEM curricula.

Future Directions and Emerging Technologies

Emerging technologies present exciting possibilities for next-generation STEM e-modules that could further enhance critical thinking development, though they also introduce new challenges requiring careful consideration. Artificial intelligence integration represents one frontier mentioned in several recent studies but not yet extensively implemented or evaluated. AI-powered adaptive systems could provide sophisticated personalization that responds to individual learning patterns, automatically adjusts difficulty levels, offers targeted feedback, and identifies misconceptions requiring remediation—capabilities exceeding what teachers can accomplish with large classes. Natural language processing could enable conversational interfaces where students explain reasoning, receive Socratic questioning to deepen thinking, and engage in dialogue that develops argumentation skills. However, concerns about algorithmic bias, data privacy, transparency of AI decision-making, and the potential for technology to replace rather than augment human teaching relationships require serious attention. Augmented and virtual reality technologies showed promising results in limited studies included in this review, enabling immersive experiences that enhance spatial reasoning, visualization of abstract concepts, and engagement with phenomena inaccessible in physical classrooms (Rahmayani 2024). As AR and VR technologies become more affordable and user-friendly, their integration into STEM e-modules likely will expand, though careful research examining cognitive benefits beyond novelty effects and potential side effects such as motion sickness or distraction from core learning objectives remains necessary.

Learning analytics and data dashboards represent another technological frontier with potential to transform how teachers monitor progress, identify struggling students requiring intervention, and make evidence-informed instructional decisions. Current e-modules capture vast amounts of data about student interactions, performance patterns, and learning trajectories that remain largely unexploited for instructional improvement. Advanced analytics could reveal patterns invisible to human observation, predict which students risk falling behind, and recommend specific interventions likely to address identified needs. However, concerns about surveillance, data security, and the potential for analytics to narrow curriculum toward easily measurable outcomes require careful governance frameworks. Gamification elements such as points, badges, leaderboards, and narrative structures appeared in some effective e-modules and may enhance motivation and engagement, particularly for students who struggle with traditional academic tasks. Research examining how game mechanics can support rather than distract from substantive learning, which students benefit most from gamified approaches, and how to avoid extrinsic motivation undermining intrinsic interest in learning remains limited (Hussein et al. 2019; Riski et al. 2025). Blockchain technology, adaptive testing algorithms, social learning platforms, and maker space integration represent additional frontiers requiring systematic investigation as they become incorporated into STEM learning environments. The field needs proactive research agendas that evaluate these innovations rigorously before they become entrenched in practice based on commercial promotion rather than evidence of effectiveness.

Recommendations for Research, Policy, and Practice

The synthesis of evidence and identification of gaps suggest several critical recommendations for advancing research, informing policy decisions, and improving classroom practice related to STEM-based e-modules for critical thinking development. Research priorities should include longitudinal studies examining long-term impacts beyond immediate post-test gains to determine whether critical thinking improvements persist over time, transfer to novel contexts, and influence subsequent academic achievement and real-world problem-solving. Large-scale randomized controlled trials with adequate power to detect differential effects across student subgroups would strengthen causal inference beyond what quasi-experimental studies can provide. Comparative effectiveness research systematically contrasting different pedagogical approaches, design features, and technological integrations within e-modules would inform design optimization. Implementation science investigations examining how e-modules are actually used in classrooms, what adaptations teachers make, what factors facilitate or hinder fidelity, and how implementation quality affects outcomes would provide crucial practical guidance. Cross-cultural research extending beyond Indonesia to diverse international contexts would enhance generalizability and illuminate how cultural factors influence effectiveness. Research employing mixed methods that combine quantitative outcomes with qualitative investigations of student experiences, cognitive processes, and meaning-making would deepen understanding of mechanisms underlying effectiveness.

Policy recommendations include strategic investments in technological infrastructure ensuring equitable access across socioeconomic contexts, comprehensive teacher professional development programs providing sustained support for pedagogical transformation rather than brief technical training, quality standards and review processes for educational technology ensuring pedagogical soundness and content accuracy before widespread adoption, and assessment system reforms aligning accountability measures with the critical thinking competencies that STEM e-modules develop. Curriculum frameworks should explicitly incorporate STEM integration and critical thinking development as core objectives rather than optional enhancements, with coherent learning progressions across grades. Funding mechanisms should support both initial adoption costs and ongoing expenses for device replacement, software updates, and continued professional development. Practice recommendations for educators include careful evaluation of e-module quality using pedagogically informed rubrics rather than superficial criteria, integration of e-modules within comprehensive instructional programs that include hands-on activities and outdoor experiences rather than replacing all traditional approaches, explicit instruction in critical thinking processes and metacognitive strategies alongside content learning, and collaborative professional learning communities where teachers share implementation experiences and problem-solve challenges collectively (Susiloningsih et al. 2025). Regular monitoring of student progress using multiple assessment methods can inform instructional adaptations, while maintaining balanced screen time through intentional scheduling prevents overexposure concerns.

CONCLUSION

This systematic literature review reveals a key finding that could only be identified through comprehensive synthesis, namely that STEM-based e-modules are not merely effective in improving learning outcomes but consistently produce educationally meaningful gains in elementary students' critical thinking skills. Across the 24 empirical studies reviewed, students demonstrated substantial improvements in analytical reasoning, evidence evaluation, information synthesis, and argument construction, with effect sizes ranging from moderate to large (d = 0.48–0.84). Notably, the strongest impacts were observed in e-modules designed using Problem-Based Learning frameworks, authentic real-world problems, interactive simulations and virtual experiments, graduated scaffolding, and formative assessments providing immediate feedback. These findings challenge earlier assumptions that the development of critical thinking at the elementary level requires prolonged interventions or is best achieved exclusively through conventional face-to-face instruction.

From a scholarly perspective, this study corroborates and extends prior research on STEM education and digital learning by providing updated and focused evidence on the intersection of STEM pedagogy, e-module design, and critical thinking development at the elementary school level. This review contributes to the literature by synthesizing fragmented empirical findings into an integrative framework that identifies pedagogical and technological features most strongly associated with critical thinking enhancement. Furthermore, it advances theoretical understanding by positioning STEM-based e-modules as a pedagogically grounded digital intervention rather than a purely technological innovation. By mapping effective design characteristics—such as PBL-STEM integration, virtual experimentation, augmented reality, and embedded formative assessment—this study enriches existing perspectives and offers a refined conceptual basis for future research and instructional design in elementary STEM education.

Despite the strength of the evidence synthesized, several limitations must be acknowledged. The reviewed studies were predominantly characterized by small sample sizes, short intervention durations, and a high concentration of research conducted within specific geographic contexts, particularly Indonesia, which constrains the generalizability of the findings. Variations in grade levels, age groups, gender representation, and critical thinking assessment instruments were limited, and most studies employed quasi-experimental designs with short-term outcome measurements. Consequently, future research should prioritize longitudinal designs, larger and more diverse samples, cross-cultural investigations, and more sophisticated assessment approaches to capture the sustainability and transferability of critical thinking gains. Further exploration of emerging technologies, including artificial intelligence and augmented reality, is also recommended to strengthen the scalability and long-term impact of STEM-based e-modules in elementary education.

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