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Digital STEM Learning to Enhance Critical Thinking in Elementary Science Education: Evidence from a Quasi-Experimental Study

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ABSTRACT

Contemporary education increasingly emphasizes the development of higher-order thinking skills, particularly critical thinking, which plays a crucial role in enabling students to analyze information, evaluate evidence, and solve scientific problems. Although STEM-based learning has been widely recognized as an effective approach to promoting inquiry and problem-solving skills, its implementation at the elementary level often remains conventional and rarely integrates digital technologies systematically. This limitation creates a significant knowledge gap regarding how digitally integrated STEM learning environments can support students' critical thinking in science education. This study aimed to examine the effect of integrating a digital STEM approach on elementary students' critical thinking skills in science learning. A quasi-experimental design with a non-equivalent control group was employed involving 60 fifth-grade students from an elementary school in Indonesia. Data were collected through a rubric-based critical thinking test, classroom observation sheets, and a teacher perception questionnaire, and analyzed using descriptive statistics and t-tests. The results revealed that the experimental group demonstrated significantly greater improvements in critical thinking than the control group ($t = 4.87$, effect size = 0.82), with notable gains across the dimensions of analysis, evaluation, and problem-solving. These findings indicate that digital STEM integration fosters more interactive learning environments that enhance students' cognitive engagement in science learning. The study contributes theoretically by strengthening the linkage between STEM Education Theory and Critical Thinking Theory. It provides practical implications for the design of technology-supported science instruction in elementary education.

Keywords: *Critical thinking; Digital STEM learning; Elementary science education; STEM education; Technology-integrated learning*

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INTRODUCTION

Contemporary educational systems are increasingly challenged to prepare learners with the higher-order cognitive competencies needed to navigate complex scientific and technological environments. Among these competencies, critical thinking has emerged as a central capability, enabling students to analyze information, evaluate arguments, and make reasoned decisions in scientific contexts. In science education, the development of critical thinking is particularly essential because scientific literacy requires learners to interpret evidence, construct explanations, and solve authentic problems grounded in empirical reasoning. In response to these demands, recent pedagogical innovations have increasingly integrated digital technologies to facilitate deeper cognitive engagement in learning processes. Empirical research indicates that technology-supported instructional strategies—such as augmented reality multimedia, inquiry-based science literacy models, and digital game-based learning—can significantly enhance students' critical thinking abilities across diverse educational contexts (Hussein et al., 2019; Sutiani et al., 2021; Syawaludin et al., 2019). Similarly, active-learning strategies implemented in science courses have been shown to strengthen students' analytical reasoning and conceptual understanding (Styers et al., 2018). Collectively, these findings highlight the growing importance of digitally supported pedagogies in fostering critical thinking within contemporary science education.

Building on these developments, scholars increasingly emphasize interdisciplinary instructional frameworks that systematically integrate digital technologies with inquiry-oriented learning processes. Within the framework of STEM Education Theory, the integration of science, technology, engineering, and mathematics has been widely recognized as a strategic approach for cultivating problem-based learning environments that stimulate higher-order thinking. Globally, education systems are therefore promoting STEM-based learning to strengthen students' analytical reasoning, scientific inquiry, and critical thinking competencies. Empirical evidence demonstrates that STEM-

E-ISSN : 3109-1059

oriented pedagogies—particularly those incorporating project-based learning and collaborative problem-solving activities—can substantially improve students' cognitive engagement and critical thinking development (Ijirana et al., 2022; Mutakinati et al., 2018). Furthermore, structured assessment instruments, such as the ELIPSS rubric, have proven effective for evaluating and reinforcing critical thinking and information processing in STEM learning contexts (Reynders et al., 2020). Additional studies also indicate that culturally contextualized STEM approaches and interdisciplinary STEM activities can further enhance students' critical and creative thinking capacities in science education (Suherman et al., 2025; Sumarni & Kadarwati, 2020). These findings collectively reinforce the potential of STEM-oriented pedagogies to support higher-order cognitive development.

While the integration of STEM learning has been extensively explored in secondary and higher education contexts, its application within elementary science education remains comparatively underdeveloped. At the primary level, science learning provides a particularly strategic context for cultivating critical thinking skills because it engages students with observation, experimentation, and evidence-based reasoning from an early stage of cognitive development. Nevertheless, empirical evidence suggests that the implementation of technology-enhanced STEM learning in elementary classrooms remains inconsistent and faces several operational challenges. Digital learning environments, including online collaborative platforms and multimedia-supported activities, have demonstrated the capacity to increase student engagement and learning persistence, with approximately 69% of learning success explained by social and cognitive presence in collaborative settings (Nungu et al., 2023). Similarly, digital game-based science learning has shown measurable improvements in elementary students' critical thinking, although these gains are not always accompanied by increases in learning motivation or self-efficacy (Hussein et al., 2019). Moreover, inquiry-based STEM models have produced significant improvements in students aged 15–16, suggesting that many existing instructional models are optimized for

 E-ISSN : 3109-1059

secondary education rather than for elementary learners (Pahrudin et al., 2021). Consequently, aligning digital STEM pedagogies with the developmental characteristics of younger learners remains a continuing challenge in science education.

Within this context, recent scholarship has examined the relationship between STEM-oriented learning and the development of higher-order thinking through diverse methodological and pedagogical approaches. A substantial body of research emphasizes project-based and inquiry-oriented STEM models as effective strategies for strengthening students' scientific creativity, problem-solving abilities, and conceptual understanding. For example, STEM-supported research–inquiry learning has been reported to enhance students' creativity through improvements in originality, flexibility, and fluency of ideas (Kirici & Bakırcı, 2021), while STEM-based project-based learning approaches have demonstrated superior outcomes in developing students' problem-solving capabilities compared with traditional discovery learning models (Purwaningsih et al., 2020). Other studies highlight the role of collaborative regulation and metacognitive scaffolding, such as SSRL-directed prompts, which facilitate shared regulation of learning processes and enhance students' engagement in problem-based environments (Michalsky & Cohen, 2021). Furthermore, interdisciplinary STEM problem-solving frameworks that link scientific inquiry to real-world contexts have been shown to improve the analytical quality of students' reasoning (Tan et al., 2022). Despite these advances, many studies rely on limited sample sizes or narrowly defined instructional interventions, leaving open questions about the consistent and scalable integration of STEM pedagogies across educational contexts.

Although the literature demonstrates the promise of technology-enhanced STEM learning, significant limitations remain in explaining how digital integration systematically contributes to the development of critical thinking in elementary science education. Several interventions have reported encouraging outcomes. For instance, digital problem-based e-books have been shown to enhance elementary students' critical thinking through multimedia-

 E-ISSN : 3109-1059

supported inquiry activities (Susanto et al., 2022), while PhET simulations significantly improve conceptual understanding and science problem-solving performance compared with traditional textbook-based instruction (Diab et al., 2024). Other initiatives—including robotics programming with Scratch Jr and digital storytelling environments—have also demonstrated potential to strengthen computational thinking and collaborative STEM competencies among young learners (Olokunde, 2021; Silva et al., 2021). In addition, narrative-based digital science–mathematics learning approaches have been found to enhance problem-solving abilities by contextualizing scientific concepts within meaningful storytelling frameworks (Wangid et al., 2021). However, these studies typically focus on isolated technological tools or specific instructional activities, offering limited insight into how digital technologies can be systematically integrated within a comprehensive STEM learning framework.

Taken together, the existing literature reveals a significant need for a more integrated pedagogical model that connects digital technologies, interdisciplinary STEM learning, and the development of critical thinking in elementary science classrooms. Building on these research gaps, this study examines the integration of a digital STEM approach into elementary science instruction and its relationship to students' critical thinking development. Specifically, the study investigates improvements in students' critical thinking abilities before and after the implementation of digitally supported STEM instruction, using a quasi-experimental design, a rubric-based assessment, and t-tests to examine learning outcomes. Responding to both theoretical and practical needs in contemporary science education, this study introduces a digital STEM integration model specifically designed for elementary science contexts. The proposed framework seeks to operationalize the relationship between STEM Education Theory and Critical Thinking Theory within classroom practice. Through this approach, the study aims to provide a more systematic and empirically grounded perspective on how digitally integrated

E-ISSN : 3109-1059

STEM learning environments can support the development of critical thinking among elementary school learners.

METHOD

Research Design

This study employed a **quasi-experimental design using a non-equivalent control group structure** to examine the effect of digital STEM integration on elementary students' critical thinking skills in science learning. This design was selected because intact classroom groups had already been established administratively, making full randomization impractical in the authentic school setting. Quasi-experimental approaches are widely used in educational intervention research, where ethical and logistical constraints prevent randomized controlled trials while still allowing causal inference about instructional effects.

The design consisted of two groups: an **experimental group that received Digital STEM Learning and a control group that received conventional science instruction**. Both groups completed a pretest before the intervention and a posttest after.

Group	Pretest	Treatment	Posttest
Experimental	O1	Digital STEM Learning	O2
Control	O3	Conventional Learning	O4

This design enabled the researchers to (1) compare baseline critical thinking levels before the intervention, (2) examine within-group improvements after instruction, and (3) determine whether the digital STEM approach produced significantly different outcomes compared with conventional instruction. The design, therefore, directly addressed the research questions regarding the effectiveness of digital STEM integration in improving students' critical thinking skills.

Research Context

The study was conducted in the context of **elementary science education** in Indonesia. The research setting was a **public elementary school**,

 E-ISSN : 3109-1059

where science (Ilmu Pengetahuan Alam) is taught as part of the national curriculum.

Participants were **fifth-grade students**, typically aged 10-11, who had previously studied basic science concepts but had limited exposure to integrated STEM instruction.

The instructional environment used a blended classroom model, combining face-to-face instruction with digital learning tools. The digital STEM intervention incorporated several instructional components, including virtual science simulations, interactive digital visualization, collaborative problem-solving activities, and simple engineering design tasks. This learning context was selected because it provides an authentic environment for implementing integrated STEM pedagogy supported by digital technologies.

Participants and Sampling

The study involved **60 elementary school students** distributed across two intact classrooms.

Group	N
Experimental	30
Control	30

Participants were selected using **cluster purposive sampling**, in which two classes were chosen based on comparable academic characteristics, similar curriculum exposure, and access to digital learning resources. After the classes were identified, **cluster-random assignment was used to determine which class would serve as the experimental group and which** as the control group.

The participants shared several key characteristics:

- Age range: **10–11 years**
- Grade level: **Grade V (elementary school)**
- Curriculum: National Elementary Science Curriculum
- Prior experience: basic familiarity with school-based digital devices

 E-ISSN : 3109-1059

Inclusion Criteria

Participants were included in the study if they:

1. were registered as active Grade V students at the participating school
2. attended the science classes during the intervention period
3. completed both the pretest and posttest assessments

Exclusion Criteria

Participants were excluded from the final analysis if they:

1. missed either the pretest or the posttest
2. were absent for more than two intervention sessions
3. provided incomplete response data.

To ensure adequate statistical power, a **power analysis using G*Power software** was conducted before data collection. Assuming an expected effect size of 0.80, a significance level of 0.05, and statistical power of 0.80, the minimum recommended sample size was 52 participants. The final sample of 60 participants, therefore, met the required threshold for statistical analysis.

Instruments

Three primary instruments were employed to collect quantitative and qualitative data: a critical thinking assessment test, a classroom observation sheet, and a teacher perception questionnaire.

Critical Thinking Assessment Test

The primary outcome measure was a **Critical Thinking Assessment Test** adapted from the **Facione critical thinking framework** and the theoretical model of **Ennis' critical thinking skills**. The instrument was designed to assess six key dimensions of critical thinking:

1. interpretation
2. analysis
3. evaluation
4. inference
5. explanation
6. self-regulation

 E-ISSN : 3109-1059

The test consisted of **10 open-ended problem-based questions** embedded within elementary science contexts. Students were required to analyse scientific problems, evaluate evidence, and propose reasoned explanations.

Responses were evaluated using a **four-point analytic rubric**:

Score	Interpretation
4	Advanced critical reasoning
3	Adequate reasoning
2	Basic reasoning
1	Limited reasoning

The instrument was adapted for the elementary science context through a process involving translation, contextual modification, and expert validation.

Classroom Observation Sheet

A structured observation sheet was used to evaluate the implementation fidelity of the digital STEM instruction and to capture qualitative classroom interaction patterns. The observation instrument measured four main constructs:

- student engagement
- collaborative problem solving
- technology integration
- engineering design activity

Each construct was evaluated using a structured observation checklist completed during each instructional session.

Teacher Perception Questionnaire

A **teacher perception questionnaire** was used to examine teachers' perspectives on the implementation of digital STEM. The questionnaire employed a **five-point Likert scale** ranging from strongly disagree (1) to agree (5) strongly. The instrument assessed four aspects of instructional effectiveness:

- perceived effectiveness of the STEM approach
- ease of instructional implementation
- student engagement during learning activities

- Perceived value of digital technologies in science learning

Instrument Validity and Reliability

Instrument validity was established through **expert judgment validation** involving three specialists in science education, STEM pedagogy, and educational measurement. These experts evaluated the instruments for content relevance, conceptual clarity, and alignment with critical thinking constructs.

Before the main study, a **pilot test was conducted with 20 elementary school students** from a different school with similar characteristics. The pilot study was used to refine question wording and assess internal consistency reliability.

Reliability analysis using **Cronbach's alpha** yielded the following values:

Instrument	Cronbach's Alpha
Critical Thinking Test	0.87
Teacher Questionnaire	0.84

Both values exceeded the recommended reliability threshold of **0.70**, indicating satisfactory internal consistency.

Data Collection Procedure

Data collection was conducted in three sequential stages over approximately **six to eight instructional sessions**.

Pretest Phase

Before the intervention began, all participants completed the **critical thinking pretest**. The purpose of the pretest was to establish a baseline for students' critical thinking abilities before exposure to the instructional treatment.

Intervention Phase

The experimental group received **Digital STEM Learning instruction** across six to eight science lessons. The instructional model integrated four STEM components:

 E-ISSN : 3109-1059

- exploration of scientific concepts using digital simulations
- collaborative problem-solving tasks
- engineering design activities
- data interpretation supported by digital tools

Students worked collaboratively to investigate science problems and design simple solutions using digital resources and engineering design processes.

In contrast, the control group received **conventional science instruction**, which primarily consisted of teacher explanations, textbook-based learning, class discussions, and simple experiments without digital integration.

To ensure **intervention fidelity**, the teacher responsible for the experimental class participated in preparatory training on digital STEM instructional strategies. Lesson plans were standardized, and classroom implementation was monitored through structured observation during each session.

Posttest Phase

At the end of the intervention period, students in both groups completed the **posttest using the same critical thinking instrument** administered during the pretest phase. This procedure allowed the researchers to measure changes in students' critical thinking performance following the instructional treatment.

Data Analysis

Both quantitative and qualitative analytical techniques were employed to address the research questions.

Quantitative Analysis

Quantitative data were analysed using **SPSS version 26**. The analysis procedure consisted of several stages.

First, **descriptive statistics** were calculated to summarize the distribution of pretest and posttest scores, including means and standard deviations.

Second, data screening procedures were conducted to ensure the assumptions of parametric testing were satisfied. These procedures included:

E-ISSN : 3109-1059

- missing data inspection
- normality testing using the **Kolmogorov–Smirnov test**
- homogeneity of variance testing using **Levene's test**
- outlier detection using **boxplot analysis**

After the assumptions were verified, two inferential statistical analyses were conducted.

1. **Paired-sample t-tests** were used to examine within-group differences between pretest and posttest scores.
2. **Independent-samples t-tests were conducted to compare posttest score**s between the experimental and control groups.

The significance level was set at **α = 0.05**. In addition to significance testing, **Cohen's d was used** to estimate the magnitude of the intervention effect.

Qualitative Analysis

Qualitative data from classroom observations and teacher interviews were analysed using **thematic analysis**. The analysis followed four stages:

1. data reduction
2. open coding
3. theme categorization
4. interpretation of emerging themes

This qualitative analysis provided complementary insights into the instructional processes and classroom interactions observed during the digital STEM implementation.

Ethical Considerations

This study adhered to standard ethical guidelines for educational research involving minors.

Before data collection, **institutional approval was obtained from the school administration and the school research ethics committee**. Written **informed consent** was obtained from school authorities, participating teachers, and the parents or guardians of all student participants.

To protect participant confidentiality, all student data were **anonymized using coded identifiers**. Individual identities were not disclosed in any reports or publications. Data were stored securely and reported only in an aggregated form to ensure the privacy and protection of all participants.

RESULT

This study investigated the effectiveness of digital STEM integration in enhancing elementary school students' critical thinking skills in science learning. The findings were derived from quantitative data obtained through critical thinking tests administered before and after the intervention, complemented by qualitative data from classroom observations and teacher interviews. Overall, the results indicate that implementing digital STEM learning was associated with measurable improvements in students' critical thinking skills. Quantitative analysis demonstrates statistically significant differences between the experimental and control groups, while qualitative findings reveal increased engagement, conceptual understanding, and problem-solving during the learning process.

The presentation of results follows the sequence of the research questions: implementation of digital STEM learning, baseline levels of students' critical thinking, the comparative impact of the intervention, the contribution of individual STEM components, and teacher perceptions of the approach's effectiveness.

Implementation of Digital STEM Learning in Elementary Science Classrooms

Classroom observations indicate that the digital STEM approach was implemented through a structured sequence of inquiry-based learning activities integrating science concepts, digital technology tools, engineering design tasks, and mathematical reasoning. The instructional model consisted of six learning stages: problem identification, digital exploration, collaborative design, experimentation, data interpretation, and reflection.

 E-ISSN : 3109-1059

Observation data suggest that digital tools, particularly simulation platforms and interactive visualization applications, were consistently integrated into science activities. These tools allowed students to explore scientific phenomena through virtual experiments and data manipulation. During the engineering design stage, students worked collaboratively to construct simple prototypes or conceptual models to address science-related problems.

Observation scores reveal high levels of student engagement in the experimental group. In particular, activities involving digital simulations and engineering design tasks demonstrated the highest levels of participation. Students frequently interacted with digital content, discussed problem-solving strategies with peers, and revised their ideas based on experimental results. These patterns suggest that integrating digital technology into STEM activities facilitated a more active, inquiry-oriented learning environment.

Baseline Levels of Students' Critical Thinking Skills

Pretest results were analysed to examine the baseline level of critical thinking skills before the intervention. Descriptive statistics indicate that the experimental and control groups exhibited relatively similar levels of critical thinking ability before the treatment was implemented.

Table 1. Pretest Scores of Critical Thinking Skills

Group	Mean	Standard Deviation
Experimental	62.4	6.81
Control	63.1	7.02

As shown in Table 1, the experimental group had a mean pretest score of 62.4, while the control group had a mean pretest score of 63.1. The relatively small difference between groups suggests comparable baseline abilities.

Further analysis using an independent samples t-test indicates that the difference between the two groups was not statistically significant ($p > 0.05$). This result suggests that both groups started the experiment with a similar level of critical thinking proficiency, thereby supporting the comparability of the groups before the treatment phase.

E-ISSN : 3109-1059

Effect of Digital STEM Learning on Critical Thinking Skills (RQ3)

Posttest results reveal substantial improvements in the critical thinking scores of students in the experimental group compared with those in the control group.

Table 2. Comparison of Pretest and Posttest Scores

Group	Pretest Mean	Posttest Mean
Experimental	62.4	82.7
Control	63.1	71.3

As presented in Table 2, the experimental group's mean score increased from 62.4 to 82.7 following the digital STEM intervention, while the control group's score increased from 63.1 to 71.3 under conventional instruction. The magnitude of improvement in the experimental group appears substantially greater than that observed in the control group.

To examine the statistical significance of these differences, an independent samples t-test was conducted. The analysis indicates a significant difference between groups ($t = 4.87$, $p < 0.001$). This result demonstrates that students who participated in digital STEM learning achieved significantly higher critical thinking scores compared with those receiving conventional instruction.

Additionally, the calculated effect size (Cohen's d) was 0.82, indicating a large effect. This finding suggests that the digital STEM intervention had a substantial impact on students' critical thinking development.

Contribution of STEM Components to Critical Thinking Development

Further analysis examined the relative contributions of each STEM component to the development of critical thinking skills. Observation data and student performance patterns reveal that engineering design and technology integration played the most prominent roles in facilitating higher-order thinking processes.

Engineering design activities required students to construct solutions, test hypotheses, and revise prototypes based on experimental evidence. These

 E-ISSN : 3109-1059

activities frequently involved cycles of analysis, evaluation, and inference, which correspond directly to critical thinking indicators.

Digital technology tools also contributed significantly by enabling interactive exploration of scientific concepts. Simulation platforms allowed students to manipulate variables, observe outcomes, and test predictions, thereby strengthening analytical reasoning.

Among the six critical thinking indicators assessed in this study, the most substantial improvements were observed in the dimensions of **analysis**, **evaluation**, and **inference**. These indicators showed the largest gains between pretest and posttest assessments in the experimental group.

Teacher Perceptions of Digital STEM Integration (RQ5)

Qualitative data from teacher interviews provide additional insights into the effectiveness of digital STEM implementation in elementary science learning. Thematic analysis identified four dominant themes that describe teachers' experiences with the instructional approach.

Table 3. Themes Emerging from Teacher Interviews

Theme	Description
Student Engagement	Students demonstrated higher participation and enthusiasm during digital STEM activities.
Concept Visualization	Digital simulations helped students understand abstract science concepts.
Problem-Solving Development	Students showed greater ability to analyse problems and propose solutions.
Digital Interaction	Technology facilitated exploration and collaborative learning.

Teachers reported that integrating digital tools significantly improved students' attention and participation in science lessons. In particular, visual simulations helped students grasp abstract scientific processes that are difficult to demonstrate through conventional experiments.

Teachers also noted that engineering-based activities encouraged students to discuss ideas, test alternative solutions, and justify their reasoning.

E-ISSN : 3109-1059

These behaviours were perceived as indicators of developing critical thinking skills during classroom activities.

Beyond the primary analyses, several patterns emerged from the data. First, students in the experimental group demonstrated more consistent improvements across all six critical thinking indicators than those in the control group. Second, classroom observation data suggest that collaborative problem-solving activities played an important role in facilitating analytical reasoning and explanation skills.

Furthermore, students appeared to rely more frequently on evidence-based reasoning when using digital simulations. During these activities, students tested hypotheses by manipulating variables and observing simulated outcomes, which may have supported deeper cognitive processing.

DISSCUSION

The findings of this study provide empirical evidence that integrating digital STEM learning into elementary science classrooms significantly enhances students' critical thinking skills. The results demonstrate statistically significant differences between students who participated in the digital STEM intervention and those who experienced conventional instruction, with a large effect size favoring the experimental group. From a pedagogical perspective, these findings indicate that integrating digital tools into interdisciplinary STEM activities creates learning conditions that stimulate analytical reasoning, conceptual exploration, and problem-solving among elementary learners. The qualitative findings further reinforce this interpretation, revealing increased student engagement, improved conceptual visualization, and more active participation in collaborative problem-solving. Collectively, these outcomes suggest that digitally supported STEM learning environments provide meaningful opportunities for students to interact with scientific concepts through inquiry, experimentation, and technological mediation, thereby fostering higher-order cognitive development in elementary science education.

 E-ISSN : 3109-1059

From a theoretical standpoint, the effectiveness of digital STEM learning observed in this study can be interpreted through the lens of constructivist learning theory and experiential learning frameworks. Constructivist perspectives emphasize that knowledge is actively constructed through learners' interactions with their environment, particularly through inquiry, experimentation, and collaborative problem-solving. In the digital STEM environment implemented in this study, students were encouraged to explore scientific phenomena through simulations, engineering design tasks, and data interpretation activities. Such learning experiences align with experiential learning principles, where students develop conceptual understanding through direct engagement with authentic problems. The use of digital simulations further allowed students to manipulate variables and visualize scientific processes that are often difficult to observe through conventional classroom experiments. Consequently, these technology-supported learning experiences likely facilitated deeper cognitive processing, enabling students to interpret information, evaluate evidence, and construct logical explanations—core components of critical thinking as conceptualized by Facione and Ennis.

The findings of this study also align with the theoretical principles underlying STEM Education Theory, which advocates integrating science, technology, engineering, and mathematics to promote interdisciplinary problem-solving and higher-order thinking. Within the digital STEM learning model applied in this research, students engaged in a sequence of inquiry-based science activities supported by digital tools and engineering design challenges. This instructional structure encouraged learners to approach scientific problems from multiple disciplinary perspectives, requiring them to analyze data, formulate hypotheses, test solutions, and evaluate outcomes. Such interdisciplinary engagement appears to have strengthened students' analytical reasoning and problem-solving skills, particularly within the dimensions of analysis, evaluation, and inference identified in the critical thinking framework. The results, therefore, support the argument that integrated STEM instruction can serve as an effective pedagogical mechanism

E-ISSN : 3109-1059

for promoting cognitive engagement and critical thinking, especially when supported by digital learning technologies.

When situated within the broader body of international research, the findings of this study demonstrate both consistency with and extension of existing literature on technology-enhanced STEM learning. Previous studies have reported that digital learning environments, including augmented reality, inquiry-based multimedia learning, and digital game-based science instruction, can significantly improve students' critical thinking skills and scientific reasoning abilities (Hussein et al., 2019; Sutiani et al., 2021; Syawaludin et al., 2019). Similarly, active learning strategies and project-based STEM instruction have been shown to enhance students' analytical reasoning and collaborative problem-solving (Ijirana et al., 2022; Mutakinati et al., 2018). The present study corroborates these findings while extending the literature by demonstrating that digitally integrated STEM instruction can produce comparable cognitive benefits within elementary science contexts, which remain underrepresented in existing research. In particular, the results suggest that younger learners can engage in meaningful STEM inquiry when instructional design integrates digital tools, collaborative learning, and structured problem-solving tasks.

In addition to confirming prior findings, this study offers new insights by highlighting the pedagogical mechanisms that mediate the relationship between digital STEM instruction and the development of critical thinking. The qualitative observations revealed that students participating in digital STEM activities demonstrated greater curiosity, discussion, and collaborative reasoning than those in conventional classrooms. These behaviors reflect elements of socio-cultural learning theory, which emphasizes that cognitive development is strongly influenced by social interaction and collaborative knowledge construction. Through group-based STEM projects and problem-solving discussions, students were able to articulate ideas, negotiate alternative explanations, and refine their reasoning processes. The integration of digital simulations further supported these interactions by providing visual

 E-ISSN : 3109-1059

representations of scientific phenomena that facilitated collective interpretation and discussion. Thus, the findings suggest that digital STEM learning not only enhances individual cognitive engagement but also fosters collaborative learning environments that support the co-construction of scientific knowledge.

From a theoretical perspective, this study also contributes to the ongoing dialogue regarding the relationship between STEM Education Theory and Critical Thinking Theory in elementary education contexts. While many studies have explored the role of STEM instruction in promoting higher-order thinking among secondary and tertiary students, relatively few have examined how these theoretical frameworks operate in elementary classrooms. The results of this research demonstrate that the integration of STEM disciplines with digital learning tools can effectively operationalize critical thinking indicators such as interpretation, analysis, evaluation, inference, and explanation among young learners. This finding suggests that elementary science education can serve as an important foundation for cultivating higher-order thinking skills when instructional designs are structured around inquiry-based STEM activities. Consequently, the study strengthens the theoretical linkage between interdisciplinary STEM pedagogy and cognitive development models of critical thinking.

Beyond its theoretical implications, the study also offers several practical implications for educational practice and policy. For classroom teachers, the results highlight the value of integrating digital tools and interdisciplinary STEM activities into science instruction to stimulate deeper student engagement and reasoning. Teachers may use digital simulations, collaborative STEM projects, and inquiry-based tasks as instructional strategies to encourage students to explore scientific concepts rather than simply receive information passively. For curriculum developers, the findings underscore the importance of embedding digital STEM learning frameworks within elementary science curricula to support the development of higher-order thinking skills from an early stage of education. At the policy level, the results

E-ISSN : 3109-1059

provide empirical support for initiatives promoting the integration of technology and STEM learning within primary education systems, particularly in efforts to prepare students with the competencies required for twenty-first-century demands.

Despite these contributions, several limitations should be acknowledged when interpreting the findings of this study. First, the research employed a quasi-experimental design without full randomization of participants, which may limit the ability to control for potential confounding variables fully. Second, the study was conducted within a single school context, and therefore, the findings may reflect contextual factors specific to the institutional environment, teacher practices, or student characteristics. Third, the intervention's duration was relatively short, which may not fully capture the long-term effects of digital STEM learning on students' cognitive development. These limitations suggest that the results should be interpreted with caution, particularly when generalizing the findings across different educational contexts.

Future research should therefore explore several avenues further to advance understanding of digital STEM pedagogy in elementary education. Longitudinal studies could examine the sustained impact of digital STEM learning on students' cognitive development and academic performance over extended periods. Additional research across multiple schools and diverse educational contexts would further strengthen the external validity of the findings and provide insights into the contextual factors that influence STEM learning effectiveness. Furthermore, future investigations may examine additional variables, such as student motivation, self-regulated learning, and collaborative engagement, to develop a more comprehensive understanding of the mechanisms by which digital STEM learning influences the development of critical thinking. By extending research in these directions, scholars can contribute to the development of evidence-based pedagogical models that transform science education and prepare students with the cognitive competencies required to meet future scientific and technological challenges.

 E-ISSN : 3109-1059

CONCLUSION

This study demonstrates that integrating digital STEM learning into elementary science education significantly enhances students' critical thinking skills. The findings indicate that students who participated in digitally supported STEM activities achieved higher levels of analytical reasoning, conceptual understanding, and problem-solving ability than those who received conventional instruction. These improvements can be attributed to the interdisciplinary nature of STEM learning combined with the use of digital simulations and collaborative inquiry activities that enable students to explore scientific phenomena more interactively. From a pedagogical perspective, the results suggest that digitally integrated STEM environments create meaningful learning experiences that encourage students to interpret evidence, evaluate ideas, and construct logical explanations—core components of critical thinking in science education.

Beyond its empirical findings, this study contributes to the theoretical and practical development of STEM-based learning in elementary education. The proposed digital STEM learning model illustrates how integrating science inquiry, technology-supported exploration, and engineering design tasks operationalizes principles from STEM Education Theory and Critical Thinking Theory in classroom practice. These insights highlight the importance of designing learning environments that actively engage students in authentic scientific problem-solving processes from an early stage of education. For educators and curriculum designers, the results underscore the potential of digital STEM pedagogy to enrich science instruction and strengthen higher-order thinking skills among young learners.

Nevertheless, the findings should be interpreted in light of several limitations, including the quasi-experimental design, the relatively limited research context, and the short duration of the intervention. Future research should therefore extend this work by implementing longitudinal designs, expanding participant diversity across multiple schools, and examining additional variables such as learning motivation, self-regulated learning, and

 E-ISSN : 3109-1059

collaborative engagement. Such investigations will help refine digital STEM pedagogical frameworks and provide deeper insights into how technology-supported STEM learning can sustainably enhance the development of critical thinking in elementary science education.

REFERENCE

Diab, H., Daher, W., Rayan, B., Issa, N., & Rayan, A. (2024). Transforming Science Education in Elementary Schools: The Power of PhET Simulations in Enhancing Student Learning. Multimodal Technol. Interact., 8, 105. https://doi.org/10.3390/mti8110105

Hussein, M., Ow, S., Cheong, L. S., & Thong, M. (2019). A Digital Game-Based Learning Method to Improve Students' Critical Thinking Skills in Elementary Science. IEEE Access, 7, 96309–96318. https://doi.org/10.1109/access.2019.2929089

Ijirana, I., Aminah, S., Supriadi, S., & Magfirah, M. (2022). Critical thinking skills of chemistry education students in team project-based STEM-metacognitive skills learning during the Covid19 pandemic. Journal of Technology and Science Education. https://doi.org/10.3926/jotse.1697

Kirici, M. G., & Bakırcı, H. (2021). The effect of STEM supported research-inquiry-based learning approach on the scientific creativity of 7th grade students. Journal of Pedagogical Research. https://doi.org/10.33902/jpr.2021067921

Michalsky, T., & Cohen, A. (2021). Prompting Socially Shared Regulation of Learning and Creativity in Solving STEM Problems. Frontiers in Psychology, 12. https://doi.org/10.3389/fpsyg.2021.722535

Mutakinati, L., Anwari, I., & Kumano, Y. (2018). Analysis of Students' Critical Thinking Skill of Middle School through STEM Education Project-Based Learning. Jurnal Pendidikan IPA Indonesia, 7, 54–65. https://doi.org/10.15294/jpii.v7i1.10495

Nungu, L., Mukama, E., & Nsabayezu, 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, 1–20. https://doi.org/10.1007/s10639-023-11607-w

Olokunde, T. (2021). Digital Storytelling as a Tool for Developing Computer Science Soft Skills in Elementary Learners: A Perspective from a STEM based Informal Learning Environment. International Journal of Computer Applications. https://doi.org/10.5120/ijca2021921394

Pahrudin, A., Misbah, M., Alisia, G., Saregar, A., Asyhari, A., Anugrah, A., & Endah, N. (2021). The Effectiveness of Science, Technology, Engineering, and Mathematics-Inquiry Learning for 15-16 Years Old Students Based on K-13 Indonesian Curriculum: The Impact on the Critical Thinking Skills. European Journal of Educational Research, 10, 681–692. https://doi.org/10.12973/eu-jer.10.2.681

 E-ISSN : 3109-1059

Purwaningsih, E., Sari, S., Sari, A., & Suryadi, A. (2020). The Effect of STEM-PjBL and Discovery Learning on Improving Students' Problem-Solving Skills of Impulse and Momentum Topic. Jurnal Pendidikan IPA Indonesia, 9, 465–476. https://doi.org/10.15294/jpii.v9i4.26432

Reynders, G., Lantz, J., Ruder, S., Stanford, C., & Cole, R. (2020). Rubrics to assess critical thinking and information processing in undergraduate STEM courses. International Journal of STEM Education, 7, 1–15. https://doi.org/10.1186/s40594-020-00208-5

Silva, R., Fonseca, B., Costa, C., & Martins, F. (2021). Fostering Computational Thinking Skills: A Didactic Proposal for Elementary School Grades. Education Sciences. https://doi.org/10.3390/educsci11090518

Styers, M., Van Zandt, P., & Hayden, K. (2018). Active Learning in Flipped Life Science Courses Promotes Development of Critical Thinking Skills. CBE Life Sciences Education, 17. https://doi.org/10.1187/cbe.16-11-0332

Suherman, S., Vidákovich, T., Mujib, M., Hidayatulloh, H., Andari, T., & Susanti, V. D. (2025). The Role of STEM Teaching in Education: An Empirical Study to Enhance Creativity and Computational Thinking. Journal of Intelligence, 13. https://doi.org/10.3390/jintelligence13070088

Sumarni, W., & Kadarwati, S. (2020). Ethno-Stem Project-Based Learning: Its Impact to Critical and Creative Thinking Skills. Jurnal Pendidikan IPA Indonesia, 9, 11–21. https://doi.org/10.15294/jpii.v9i1.21754

Susanto, T., Dwiyanti, P. B., Marini, A., Sagita, J., Safitri, D., & Soraya, E. (2022). E-Book with Problem Based Learning to Improve Student Critical Thinking in Science Learning at Elementary School. Int. J. Interact. Mob. Technol., 16, 4–17. https://doi.org/10.3991/ijim.v16i20.32951

Sutiani, A., Situmorang, M., & Silalahi, A. (2021). Implementation of an Inquiry Learning Model with Science Literacy to Improve Student Critical Thinking Skills. International Journal of Instruction. https://doi.org/10.29333/iji.2021.1428a

Syawaludin, A., Gunarhadi, G., Rintayati, P., Prof., T. T., & Dr., T. T. (2019). Development of Augmented Reality-Based Interactive Multimedia to Improve Critical Thinking Skills in Science Learning. International Journal of Instruction. https://doi.org/10.29333/iji.2019.12421a

Tan, A.-L., Ong, Y. S., Ng, Y. S., & Tan, J. H. J. (2022). STEM Problem Solving: Inquiry, Concepts, and Reasoning. Science & Education, 32, 381–397. https://doi.org/10.1007/s11191-021-00310-2

Wangid, M., Putra, C. A., & Rudyanto, H. (2021). The Science-Math Stories Based on Digital Learning: Digital Literacy Innovation in Increasing Ability to Solve Problems. Int. J. Emerg. Technol. Learn., 16. https://doi.org/10.3991/ijet.v16i09.22039