JURNAL PENDIDIKAN MATEMATIKA DAN IPA

Vol. 17, No. 2 (2026) h. 223-234

http://jurnal.untan.ac.id/index.php/PMP

IMPLEMENTATION OF STEM-BASED DIGITAL TRANSFORMATION TO IMPROVE SCIENCE LITERACY OF JUNIOR HIGH SCHOOL STUDENTS IN PADANGSIDIMPUAN CITY

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DOI: http://dx.doi.org/10.26418/jpmipa.v17i2.99085

Abstract

The low level of science literacy among junior high school students, especially in regions such as Padangsidimpuan City, remains a major obstacle to delivering education that meets the demands of the 21st century. Digital transformation, combined with the STEM (Science, Technology, Engineering, and Mathematics) approach, is considered a promising solution by integrating technology into instruction and enhancing students' critical thinking abilities. This study aims to: (1) assess the science literacy levels of junior high school students in Padangsidimpuan City before and after the implementation of the instructional intervention; (2) describe the implementation of science learning designed around digital transformation and the STEM approach; and (3) evaluate its effectiveness in improving science literacy. A mixed-methods approach was adopted, utilizing a quasi-experimental design with a nonequivalent control group. Data were collected through science literacy assessments, classroom observations, student questionnaires, and interviews with both students and teachers. Quantitative data were analyzed using t-tests and normalized gain (N-Gain), while qualitative data were interpreted through thematic analysis. The findings demonstrate a significant increase in science literacy among students in the experimental group compared to those in the control group, with an average N-Gain of 0.62, categorized as moderate to high. The results suggest that science instruction incorporating digital transformation and the STEM

Received : 2025-09-19
Revised : 2026-02-10
Accepted : 2026-02-12

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approach is effective in improving students' science literacy and promoting active participation in the learning process. Moreover, this study produced a contextual digital learning module and offered policy recommendations to support science and technology-oriented education.

Keywords**:** *digital transformation, STEM, science literacy, science education, Padangsidimpuan*

INTRODUCTION

The rapid advancement of information and communication technology (ICT) has brought significant changes across various aspects of life, including the field of education. The digital era demands a transformation in the education system that goes beyond content mastery, emphasizing 21st-century skills such as critical thinking, problem-solving, collaboration, and digital literacy. Digital transformation in education has become a key strategy to improve both the quality of the learning process and outcomes, particularly in science education, which emphasizes scientific process skills and deep conceptual understanding [1].

Digital transformation in education entails a paradigm shift from conventional instruction to technology-based and digital content-driven learning. Interactive learning media, digital platforms, and technology-based learning resources serve as effective alternatives to foster students' active engagement. However, the implementation of digital transformation in regions such as Padangsidimpuan City still faces several challenges, including limited technological infrastructure, inadequate availability of devices, and insufficient teacher competencies in integrating ICT into teaching practices [2].

In line with digital transformation, integrative and contextual teaching approaches are also essential. One relevant and proven effective approach to enhancing students' science literacy is the STEM (Science, Technology, Engineering, and Mathematics) approach. STEM not only emphasizes the mastery of conceptual knowledge but also fosters higher-order thinking skills and real-world application of scientific understanding. Brown [3] emphasized that STEM is not merely an acronym but a framework for building integrated interdisciplinary understanding.

Previous studies have shown that the STEM approach can significantly improve student motivation, problem-solving skills, and science literacy [4]–[6]. Science literacy itself refers to the ability to use scientific knowledge to identify issues, explain phenomena scientifically, and draw evidence-based conclusions [1]. In the context of science learning at the junior high school level, strengthening science literacy is crucial in preparing students to face both global and local challenges that are rooted in science and technology.

Although digital transformation and the STEM approach have been prioritized in national education policies, their implementation in junior high school science learning still faces

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various constraints, particularly in areas with limited technological infrastructure [7], [8]. The gap between policy directions and on-the-ground realities poses a serious challenge to achieving equitable improvements in science education quality.

Therefore, this study aims to address the following research questions: (1) What is the level of science literacy among junior high school students in Padangsidimpuan City before and after the implementation of digital STEM-based learning? (2) How is the implementation process of digital transformation-based science learning using the STEM approach carried out in the local context of Padangsidimpuan? and (3) To what extent is the effectiveness of this learning model in improving students' science literacy?

The main objectives of this study are to: (1) analyze the level of students' science literacy before and after the implementation of digital STEM-based instruction; (2) describe the contextual implementation of science learning through digital transformation; and (3) measure the effectiveness of the learning approach in enhancing students' science literacy. The findings of this study are expected to contribute theoretically to the development of innovative STEM-based science learning models and practically to provide recommendations that support the acceleration of digital transformation in education, particularly in resource-constrained areas.

METHOD

Research Design and Approach

This study employed a mixed methods approach, integrating both quantitative and qualitative data to obtain a comprehensive understanding of the investigated phenomenon. The quantitative component utilized a quasi-experimental design, specifically the Nonequivalent Control Group Design, where the experimental and control groups were not randomly assigned but shared comparable initial characteristics. This design was combined with a qualitative approach involving classroom observations and interviews to explore the implementation process and participants' perceptions in depth.

Research Site and Participants

The study was conducted at three public junior high schools (Sekolah Menengah Pertama or SMP) in Padangsidimpuan City, selected purposively based on the following criteria: (1) availability of basic ICT infrastructure, (2) willingness of science teachers to collaborate, and (3) diverse student backgrounds representing the local context. The sample consisted of six classes—three experimental and three control—with a total of 180 students. The experimental classes received STEM-based science instruction supported by digital transformation, while the control classes followed conventional teaching methods.

Research Instruments

To comprehensively capture the data needed to address the research objectives, this study employed four primary research instruments, each designed to measure different aspects of the learning process and outcomes. These instruments are as follows:

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1. Science Literacy Test. The test was developed based on the PISA (Programme for International Student Assessment) science literacy framework, which includes indicators such as: explaining scientific phenomena, evaluating and designing scientific investigations, and interpreting scientific data and evidence. The instrument consisted of 20 items, including multiple-choice and short-response questions. Validity was established through expert judgment, and reliability was confirmed through a pilot study using Cronbach's Alpha.
2. Student Response Questionnaire. A structured questionnaire was designed to measure students' perceptions of STEM-based and digitally integrated learning. The questionnaire included indicators such as student engagement, ease of technology use, and perceived understanding of science concepts.
3. Classroom Observation Sheet. Used to assess the implementation fidelity of STEM learning, students' participation, and the integration of digital tools throughout the instructional process.
4. Interview Guidelines. Semi-structured interviews were conducted with science teachers and selected students to explore experiences, perceptions, and challenges during the implementation of digital STEM-based learning.

To ensure the clarity of the digital intervention, the STEM-based instruction in the experimental classes integrated several digital tools in a structured manner. Canva was used to deliver animated concept videos and visual learning materials that introduced scientific phenomena in contextual settings. Interactive simulations supported students in exploring scientific processes and testing variables virtually, enabling inquiry-based learning. Wordwall functioned as a game-based formative assessment tool to reinforce understanding and maintain student engagement.

The instructional sequence followed five stages: concept introduction through multimedia, exploration using simulations, engineering design tasks, mathematical analysis, and formative evaluation via digital quizzes. Teachers acted as facilitators to guide students in using digital tools meaningfully within STEM learning activities.

Data Collection Techniques

Quantitative data were collected through pre-tests and post-tests administered to both experimental and control groups, as well as from the student questionnaires distributed after the intervention. Qualitative data were gathered from field notes during classroom observations and interview transcripts. The study was carried out over one academic semester, with the intervention conducted over eight instructional sessions in the experimental classes.

Data Analysis Techniques

1. Quantitative Data Analysis

Descriptive statistics were used to examine mean scores, standard deviations, and score distributions. A

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paired sample t-test was used to assess differences between pre-test and post-test scores within each group. An independent sample t-test was employed to compare post-test scores between the experimental and control groups. The normalized gain (N-Gain) was calculated to determine the relative improvement in student understanding.

2. Qualitative Data Analysis

A thematic analysis approach was adopted, involving the stages of transcription, open coding, categorization, and meaning interpretation. This enabled the identification of contextual factors, instructional processes, and variables influencing the success of the digital STEM learning model.

RESULT AND DISCUSSION

This section presents the research findings based on the previously formulated objectives, including: (1) analysis of students' science literacy levels; (2) implementation of science learning based on digital transformation and the STEM approach; and (3) evaluation of the effectiveness of the learning model in enhancing science literacy.

Students' Science Literacy Levels Before and After the Intervention

Based on the pre-test results, the science literacy level of junior high school students in Padangsidimpuan City was relatively low. The average pre-test score in the experimental class was 46.2 (SD = 8.4), while in the control class it was 45.7 (SD = 9.1). Prior to hypothesis testing, the data were confirmed to be normally distributed (Shapiro–Wilk, $p > 0.05$) and homogeneous (Levene's test, $p > 0.05$), indicating that parametric analysis assumptions were met. An independent sample t-test showed no significant difference between the two groups ($p > 0.05$), indicating that the initial capabilities of students were comparable. Post-test results demonstrated a significant improvement. The average post-test score in the experimental class increased to 79.6 (SD = 7.2), while the control class achieved only 62.1 (SD = 8.7). The independent t-test indicated a statistically significant difference between the two groups ($p < 0.001$). The magnitude of this difference was substantial, with a large effect size (Cohen's d = 1.84), indicating a strong practical impact of the digital-STEM intervention on students' science literacy.

Analysis using the Normalized Gain (N-Gain) revealed that the experimental class achieved an average gain of 0.62 (categorized as moderate–high), while the control class obtained only 0.28 (categorized as low–moderate), as summarized in the table 1.

Table 1. Improvement in Science Literacy Using N-Gain Analysis

Group	Mean Pre-test	Mean Post-test	N-Gain	Category
Experimental	46.2	79.6	0.62	Moderate–High
Control	45.7	62.1	0.28	Low–Moderate

Source: Pre-test and post-test results, 2025

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In terms of literacy level distribution, 68% of students in the experimental class reached the "proficient" category after the intervention, compared to only 29% in the control group. The proportion of students in the "low literacy" category decreased from 54% to 11% in the experimental class, demonstrating a meaningful shift in literacy achievement levels.

These findings are consistent with previous research conducted by Sole [9] and Sulistiyowati [10], which confirmed that the STEM-based learning approach significantly enhances students' science literacy, particularly in the areas of scientific concept application and problem-solving skills. The STEM approach emphasizes interdisciplinary integration, enabling students to understand science within real-world contexts rather than merely as conceptual memorization.

Khairani [11] also emphasized that STEM is not solely an instructional method, but a conceptual framework that fosters interdisciplinary thinking and project-based problem solving. In the present study, the integration of STEM into science topics contextualized through local phenomena contributed to more meaningful learning and increased students' conceptual understanding.

According to the OECD [1] PISA framework, science literacy includes not only content understanding, but also the ability to reason scientifically, evaluate evidence, and make informed decisions. Therefore, the improvement in students' scores in the experimental class reflects not only mastery of the subject matter but also development of essential scientific competencies for the 21st century.

The findings are further supported by Shaik et al. [12], who stated that the use of digital media in science instruction enhances students' attention, participation, and comprehension of complex topics. Digital tools such as simulations and interactive modules serve as cognitive scaffolds, helping students to visualize abstract concepts that are often difficult to grasp through conventional methods [13]. Pedagogically, these results align with Vygotsky's constructivist theory, which posits that learning occurs more effectively when students construct knowledge through social interaction and the use of mediating tools, including digital technologies. The teacher's role as a facilitator, rather than the primary source of knowledge, also supports the optimal development of students' zone of proximal development (ZPD).

Implementation of STEM Learning Based on Digital Transformation

The STEM-based science learning model was implemented across eight instructional sessions using Canva-based digital modules, Wordwall interactive quizzes, and virtual simulations. Learning activities integrated real-life local contexts, such as analyzing traditional tools from Tapanuli in the topic of pressure, to connect scientific concepts with students' environments.

Observation data indicated a high level of implementation fidelity, with an overall mean score of 3.52 (very good category). Student engagement (3.71) and collaborative interaction (3.64) were the most prominent aspects, while teacher facilitation (3.48) and

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digital tool integration (3.56) also demonstrated strong instructional quality. These results confirm that digital-STEM learning can be implemented effectively even in schools with limited resources.

Table 2. Observation Results of Digital-Based STEM Learning Implementation

Observed Aspect	Description of Findings
Student Enthusiasm and Engagement	Students showed high enthusiasm and active participation during lessons using digital tools.
Group Participation and Interaction	Group discussions improved significantly, with students actively sharing ideas and collaborating on STEM projects.
Teacher's Role in the Classroom	Teachers functioned as facilitators, guiding students' exploration instead of delivering information.

Source: Classroom observation sheet, field notes, and researcher documentation, 2025

Figure 1. Growth profiles of bacterial isolates IS-1, IS-2, and IS-3 in media supplemented with Pb metal at concentrations ranging from 150 to 350 ppm (Only use capital letters at the beginning of the sentence)

Overall, the implementation was rated very good (≥85%), demonstrating the feasibility and effectiveness of integrating digital-based STEM learning in junior high school science classes, even in resource-limited settings. These findings align with Lestari et al. [14], who found that the use of Wordwall significantly increased students' motivation and engagement in basic science learning, confirming its potential as an effective educational medium in middle school contexts.

Recent evidence corroborates these findings. For instance, Lin et al. , [15] found that well-integrated digital STEM interventions significantly improve student engagement and conceptual understanding in science classrooms across diverse contexts. Similarly, Khaeroningtyas et al. [16] reported that technology-enhanced STEM activities increase student motivation and collaborative problem-solving skills, especially in resource-limited settings.

Students' and Teachers' Perceptions and Experiences

Student responses from the post-intervention questionnaire are illustrated in the diagram 1.

The results indicate a very positive perception. Approximately 88% of students agreed that the learning process was more engaging and easier to understand, reflecting improvements in affective aspects and overall engagement. This aligns with the principle of active learning within constructivist theory, which emphasizes activity, interaction, and reflection as keys to meaningful learning [17].

Furthermore, 84% of students reported increased confidence in expressing ideas and participating in discussions, indicating enhanced scientific communication skills.

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Additionally, 90% of students acknowledged that digital media significantly helped them understand science concepts, particularly abstract topics that are typically difficult to visualize through conventional instruction. One student explained, *"Simulations made it easier to understand how pressure works, because we could directly observe the process."* A teacher also stated, *"Using Canva and Wordwall helped structure lessons more clearly, and students became more active compared to conventional classes."*

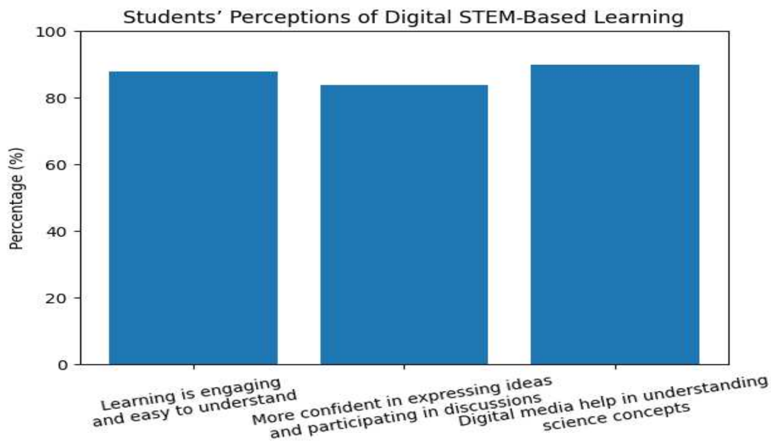

Figure 1. Student Questionnaire Results

The use of simulations and interactive modules exemplifies technology as mindtools, as proposed by Jonassen [18], allowing students to learn *with media*, rather than merely *from media*, thereby improving both engagement and cognitive outcomes.

Interviews with teachers revealed that the digital-STEM approach enabled more structured and 21st-century skills-oriented lesson planning. Teachers stated that integrating digital media and interdisciplinary approaches encouraged them to design learning activities emphasizing scientific processes, critical thinking, and problem solving. These findings support the arguments of Scagliola et al. [19] and Wu [20], who highlighted that teachers in 21st-century classrooms must shift from being information providers to facilitators of higher-order thinking and digital literacy development.

Teachers also noted that this approach motivated students to become self-directed learners, especially when given autonomy to explore interactive media and digital learning resources. This observation is consistent with findings by Kamila & Maryani [21], who demonstrated that STEM-based digital learning enhances self-regulated learning and students' problem-solving abilities in science education. Project-based and problem-based learning inherent in STEM also provides students with authentic learning experiences, which improve engagement and learning initiative [22]–[25].

Despite these successes, challenges remain—particularly in terms of internet access and availability of ICT devices, especially for students from lower-income families. This discussion aligns with the constructivist perspective that emphasizes the importance of student engagement in real-world contexts and technology as a cognitive support tool. Therefore, digital transformation in education should not be viewed solely as a technical shift, but as a pedagogical strategy to improve the quality of science learning interactions and conceptual understanding [1], [26], [27].

CONCLUSION

This study provides empirical evidence that the implementation of digital transformation based on the STEM approach in science learning significantly enhances junior high school students' science literacy in Padangsidimpuan City. Learning activities designed through the integration of interactive digital media and interdisciplinary approaches (science, technology, engineering, and mathematics) were effective in promoting active participation, improving conceptual understanding, and fostering students' critical thinking skills. Specifically, the conclusions of this study are as follows:

1. The students' science literacy level before the intervention was categorized as low, with no statistically significant difference between the experimental and control groups.
2. The implementation of STEM-based learning supported by digital media successfully created a more interactive, contextual, and meaningful learning environment.
3. A statistically significant improvement in students' science literacy was observed in the experimental group compared to the control group, as evidenced by the post-test results and N-Gain scores categorized as moderate to high.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Direktorat Penelitian dan Pengabdian kepada Masyarakat (DPPM), Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for providing research funding under the 2025 fiscal year. Special thanks are also extended to the Padangsidimpuan City Education Office and all participating schools for their valuable support and cooperation throughout the research process.

This section concludes and provides policy implications, if any, of the study. The conclusion(s) should be at the same order with ones discussed.

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