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Technology-Enhanced STEM-PjBL: A Pathway to Strengthen Students' Critical Thinking in Understanding the Nature of Science through Social Phenomena

Sukarno[1], Elza Triani[2], Miftahul Zannah Azzahra[3], Ahmad Mansur Nawahdani[4]
[1]Universitas Islam Negeri Fatmawati Sukarno Bengkulu, Bengkulu, Indonesia
[2,3,4]Cahaya Ilmu Cendekia Publisher, Bengkulu, Indonesia

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ABSTRACT

Purpose of the study: This study aims to analyze the influence of STEM-PjBL learning integrated with technology media on students' critical thinking skills on the material of the Nature of Science and Scientific Methods in the context of social phenomena, and to see the effectiveness of this approach in improving students' scientific reasoning.

Methodology: The study used a mixed methods sequential explanatory design. Quantitative data were obtained through critical thinking tests and questionnaires, while qualitative data were obtained through interviews and observations. Analysis included normality, homogeneity, t-tests, ANOVA, and effect size tests using SPSS. Learning was supported by digital simulations, virtual experiment applications, and technological devices in the implementation of STEM-PjBL..

Main Findings: The results showed a significant increase in critical thinking skills in the experimental class compared to the control class. Posttest scores, gain scores, and effect size (d = 1.58) indicated a significant effect. Qualitative findings revealed increased student engagement, ability to interpret data through digital media, self-reflection, and more effective application of scientific methods during the project compared to conventional learning.

Novelty/Originality of this study: This research offers novelty through the simultaneous integration of STEM-PjBL, interactive technology media, and basic material on the Nature of Science within the context of social phenomena, which has rarely been studied before. This study also simultaneously assesses critical thinking and science process skills, thus providing a new contribution to the development of technology-based science learning to strengthen students' scientific abilities.

Corresponding Author:
Sukarno,
Universitas Islam Negeri Fatmawati Sukarno Bengkulu,
Jl. Raden Fatah, Kelurahan Pagar Dewa, Kecamatan Selebar, Kota Bengkulu 38211, Bengkulu, Indonesia
Email: sukarno01@gmail.com

1. INTRODUCTION

Advancements in science and technology require students to possess higher-order thinking skills and scientific process skills in order to respond effectively to various real-world problems. Science learning in schools is no longer sufficient when it focuses merely on conceptual mastery; it must also cultivate the ability to observe, evaluate information, identify problems, and carry out scientific procedures systematically [1]-3]. In the topic *Nature of Science and the Scientific Method*, students are expected to understand how scientific knowledge is produced through observation, experimentation, and drawing conclusions [4]-[6]. However, in practice, instruction on this topic is often delivered theoretically with minimal hands-on experience, resulting in students' critical thinking skills and scientific process skills not developing optimally [7]-[9].

On the other hand, the STEM (Science, Technology, Engineering, and Mathematics) approach provides opportunities for teachers to connect scientific concepts with technology, engineering, and project-based problem solving [10], [11]. Integrating STEM into instruction has been shown to enhance creativity, technological literacy, and students' problem-solving abilities [12]-[14]. When combined with Project-Based Learning (PjBL), students are encouraged to design projects, investigate phenomena, and produce products relevant to real-life contexts. This approach is considered effective for improving critical thinking and scientific process skills because it positions students as active agents in scientific inquiry.

The integration of technological media such as digital simulations, virtual experiment applications, or collaborative platforms has also become increasingly important in 21st-century learning [15], [16]. Technology enables students to observe phenomena that are difficult to observe directly, design experiments visually, and facilitate communication and documentation of scientific processes [17]-[19]. Although many studies show that digital media can enhance engagement and conceptual understanding, research that specifically combines STEM-PjBL with technological media in teaching the nature of science and scientific method particularly in the context of social phenomena remains limited [20], [21].

Although the literature demonstrates that project-based approaches within the STEM framework (STEM-PjBL/STEAM) can improve scientific literacy, creativity, and problem-solving skills, most empirical evidence focuses on applied topics (e.g., physics, biology, technology) and outcomes such as conceptual achievement or collaborative skills, rather than specifically on understanding the *nature of science* (NOS) [22]. Moreover, while the integration of technological tools such as virtual laboratories and interactive simulations has been documented as effective for improving conceptual understanding and access to experimentation, review studies highlight limitations of these technologies when the educational objective is to develop real practical skills or metacognitive aspects of NOS [23]. Furthermore, ERIC reviews and meta-analyses on PjBL/STEM show substantial variation in intervention designs and outcome measures, leaving very few studies that intentionally integrate all three elements simultaneously: (1) interdisciplinary STEM-PjBL, (2) interactive technological media, and (3) explicit focus on the nature of science and the scientific method while measuring their combined impact on critical thinking and scientific process skills [24], [25]. Accordingly, this study addresses an important gap in the literature by providing empirical evidence on the effectiveness of an integrated instructional model (STEM-PjBL with technology) applied to foundational content about how science is constructed and practiced an area that has been relatively underexplored. The lack of comprehensive studies examining the integration of STEM-PjBL and technological media in fundamental science topics constitutes the research gap of this study.

This research offers novelty by integrating three key components of 21st-century learning simultaneously: the STEM-Project Based Learning (STEM-PjBL) approach, the use of interactive technological media (such as virtual laboratories or digital modules), and the application of these elements to foundational content regarding the nature of science and the scientific method within the context of social phenomena. As shown by systematic reviews, PjBL-STEM models are consistently associated with enhanced scientific literacy, problem-solving, and other 21st-century skills [26], [27]. While many STEM-PjBL studies focus on applied topics such as biology or chemistry and primarily assess cognitive aspects or literacy outcomes, few examine how this model can deepen students' understanding of how science is built that is, the nature of science and scientific method leading to metacognitive aspects such as scientific epistemology often being overlooked. This explains why the topic "nature of science and scientific method" receives limited attention in innovative instructional design.

In contrast, studies combining interactive technological media with STEM (e.g., virtual labs) have demonstrated strong potential to enhance scientific literacy, student engagement, and learning motivation [28]. However, most studies focus on scientific literacy or conceptual understanding rather than leveraging interactive media to explicitly explore the nature of science or the scientific method. For example, virtual laboratory studies in biology learning have shown improvements in critical thinking when students learn through STEM and virtual labs, but the focus remains on applied biological concepts [29].

The urgency of this research lies in the pressing need within education to strengthen students' ability to understand scientific processes authentically amid the rapid digitalization of learning. Technological advancements and the growing complexity of social phenomena demand that students not only understand scientific concepts but also employ scientific approaches to analyze real-world problems [30], [31]. However, the teaching of the nature of science in schools remains predominantly declarative and lacks investigative experiences that allow students to develop higher-order thinking skills [32], [33]. Integrating technological media within the STEM-PjBL model becomes a relevant solution to increase engagement, facilitate virtual experimentation, and present abstract phenomena more concretely. Therefore, this research is important for offering an innovative instructional model that can enhance the quality of science education while supporting technology-enhanced educational transformation.

Accordingly, this study aims to analyze the effect of STEM-PjBL learning integrated with technological media on students' critical thinking skills in the topic of the nature of science and the scientific method in the context of social phenomena. The findings are expected to contribute to the advancement of innovative science learning models, particularly in maximizing the role of technology and integrated approaches to improve students' scientific competencies.

2. RESEARCH METHOD

2.1. Type of Research

This study employed a mixed-method approach with a *sequential explanatory design* [34]-[36]. In the first stage, quantitative data were collected and analyzed to determine the effect of STEM-PjBL learning integrated with technological media on students' critical thinking skills and scientific process skills. Subsequently, the qualitative stage was conducted to deepen, clarify, and validate the quantitative findings through interviews and observations [37]-[39]. This mixed-method approach was chosen to ensure comprehensive results and to provide an in-depth understanding of both the learning process and its impacts.

2.2. Population and Research Sample

The population of this study consisted of all students at a secondary school who were studying the topic Nature of Science and the Scientific Method. This population was selected because the topic serves as a foundational component in science learning and is essential for understanding scientific processes and their applications in daily life. The sample was determined using cluster random sampling, in which two classes were randomly selected to serve as the experimental and control groups [40], [41]. The experimental class received STEM-PjBL instruction integrated with technological media, whereas the control class was taught using conventional methods typically applied by the teacher. Each class consisted of 30 students. For the qualitative phase, a number of students were selected using purposive sampling, involving six to ten participants representing high-, medium-, and low-achieving groups [42]-[44]. Additionally, one science teacher was included to provide supporting information regarding the implementation of instruction and students' responses to the applied learning model.

2.3. Instruments and Data Collection Techniques

The instruments in this study were designed to obtain both quantitative and qualitative data comprehensively [45], [46]. Quantitative data were collected through a critical thinking test, constructed based on relevant theoretical indicators [47], [48]. The critical thinking test consisted of open-ended items measuring indicators of interpretation, analysis, inference, evaluation, explanation, and self-regulation. In addition, a student response questionnaire was administered to capture students' perceptions of the technology-based STEM-PjBL instruction. For the qualitative phase, data were gathered through in-depth interviews [49]-[51]. The use of multiple instruments enabled the researchers to obtain a more holistic understanding of the processes and impacts of the implemented learning model. The instrument blueprint used in this study is as follows:

Table 1. Blueprint of the Critical Thinking Instrument

No	Indicator	Description of Ability	Item Format
1	Interpretation	Identifying problems and understanding information	Contextual open-ended question
2	Analysis	Connecting evidence and arguments	Phenomena-based open-ended item
3	Inference	Drawing logical conclusions from data	Case analysis
4	Evaluation	Evaluating the accuracy of information	Table/graph-based open-ended item
5	Explanation	Explaining reasons and thinking processes	Reasoning-based open-ended item
6	Self-regulation	Reflecting on decisions and thinking processes	Written reflection

Table 2 below presents the outline of the interview instrument in this study.

Table 2. Interview Instrument Grid

Aspects Revealed	Indicators	Interview Question Focus
Student Engagement in STEM-PjBL Learning	a. Active participation in group discussions	Students' experiences discussing and completing projects
	b. Initiative in asking questions and expressing opinions	Students' habits of asking questions/expressing ideas during learning
Critical Thinking Development	a. Ability to analyze problems	How students understand and solve project problems
	b. Ability to evaluate and reflect	How students assess work results, data, and experimental procedures

	c. Evidence-based decision-making	Students' experiences determining steps or solutions based on data
The Role of Technology Media in Learning	a. Ease of understanding concepts	Use of applications, simulations, or digital tools during projects
	b. Technological support in data analysis	Use of graphs, data visualizations, or simulations
Application of the Nature of Science and the Scientific Method	a. Understanding of the steps of the scientific method	How students understand the steps of observation, hypothesis, experimentation, and analysis
	b. Application of the scientific method during the project	Concrete examples of the application of the scientific method in STEM-PjBL activities
Student Perceptions of Learning Models	a. Interest and attention during learning	Description of students' feelings during the project
	b. Benefits of learning for understanding the material	Student perceptions of the impact of learning models on conceptual understanding
Obstacles During Learning	a. Technical constraints	Difficulties using technology media
	b. Non-technical constraints	Time, group coordination, difficulty understanding instructions

2.4. Data Analysis Techniques

The data analysis techniques in this study were adapted to the mixed methods approach used. In the quantitative section, the analysis began with prerequisite tests, namely normality and homogeneity tests, to ensure the data met parametric statistical assumptions [52], [53]. Next, an independent t-test or ANOVA was conducted, depending on the number of dependent variables, to examine differences in critical thinking skills and science process skills between the experimental and control classes. In addition, an effect size calculation was performed to assess the strength of the learning model's influence. In the qualitative phase, data were analyzed using the Miles and Huberman model, which encompasses data reduction, data presentation, and conclusion drawing [54], [55]. The results of the qualitative analysis were used to strengthen, explain, and provide context for the quantitative findings, thus gaining a deeper understanding.

2.5. Research Procedures

The research procedure was carried out through several systematic stages. The first stage was preparation, which involved developing STEM-PjBL learning tools integrated with technology media, developing test instruments and questionnaires, and validating the instrument content with science education experts and educational technology experts. The second stage was the implementation of the quantitative research, beginning with a pretest administered to both classes to determine students' initial abilities. Next, the experimental class participated in technology-based STEM-PjBL learning through project activities, the use of digital simulations, virtual experiments, and contextual problem-solving, while the control class participated in conventional learning according to the teacher's method. After the learning series was completed, both classes were given a posttest [56]-[58]. The third stage was qualitative data collection, which included observing student activities during the project, interviewing students and teachers, and collecting documentation as supporting evidence. The final stage was analysis and interpretation, where quantitative and qualitative data were analyzed separately and then integrated to obtain comprehensive conclusions regarding the effectiveness of the applied learning. The research procedure can be seen in the image below:

Figure 1. Research Procedure

3. RESULTS AND DISCUSSION

3.1. Descriptive Statistics of Critical Thinking Skills

The following table presents the pretest and posttest scores for critical thinking skills in the experimental and control classes:

Table 3. Descriptive Statistics of Students' Critical Thinking Abilities

Group	N	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Gain Score
Experiment	30	48.60 ± 9.12	82.47 ± 7.35	33.87
Control	30	47.93 ± 8.74	70.10 ± 8.51	22.17

Table 3 shows that students' critical thinking skills in the experimental class increased significantly compared to the control class. The pretest scores of both groups were relatively equivalent (experimental 48.60; control 47.93), indicating that their initial abilities were not significantly different. However, after being given technology-based STEM-PjBL learning treatment, the posttest score of the experimental class increased to 82.47, while the control class only reached 70.10. The gain score of the experimental class (33.87) was also significantly higher than that of the control class (22.17), so descriptively, it appears that the learning model has a strong positive impact on improving critical thinking skills.

3.2. Results of Difference Test (t-Test)

Table 4. Results of the Posttest t-Test of Critical Thinking Skills

Variable	t-count	Sig (p)	Description
Critical Thinking	5.421	0.000	There is a significant difference

The t-test results in Table 4 show that the calculated t-value = 5.421 is greater than the t-table and the p-value = 0.000 < 0.05, so it can be concluded that there is a significant difference between students' critical thinking skills in the experimental class and the control class. This finding confirms the previous descriptive analysis that the implementation of STEM-PjBL integrated with technology media makes a significant contribution to improving students' critical thinking skills.

3.3. Effect Size (Cohen's d)

Table 5. Calculation of Effect Size of Critical Thinking Ability

Group	Mean	SD
Experiment	82.47	7.35
Control	70.11	8.51

Cohen’s d = 1.58 (very large category)

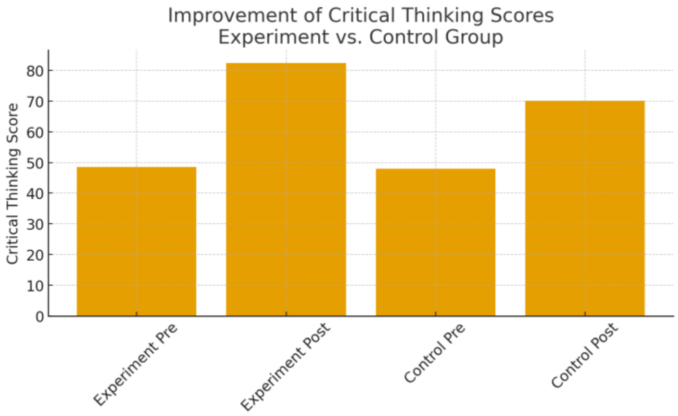

Figure 2. Score Improvement Graph

The effect size value of 1.58 indicates that the influence of technology-based STEM-PjBL instruction on critical thinking skills falls into the “very large” category. This means that the model not only produces statistically significant improvements but also generates a strong practical impact on enhancing students’ critical thinking abilities. The findings show that STEM-PjBL learning supported by technology media significantly improves students’ critical thinking skills. The substantial increase observed in the experimental class compared to the control class demonstrates that technology-integrated project-based learning is capable of creating richer, more contextual, and cognitively challenging learning experiences. STEM-PjBL encourages students to formulate problems, analyze information, construct hypotheses, evaluate evidence, and communicate project outcomescore indicators of critical thinking.

The integration of technology media such as digital simulations, project design platforms, and scientific visualization tools enables students to explore scientific concepts more deeply through clearer and more interactive representations of phenomena [59]-[61]. Technology also supports independent exploration, visual data validation, and the development of arguments grounded in empirical evidence. These findings align with previous research, which has shown that technology enhances conceptual understanding and cognitive engagement in inquiry- and project-based learning activities [62], [63]. The large gain score difference and the exceptionally high effect size further indicate that the implemented model provides not only statistically significant effects but also strong practical impacts on the development of higher-order thinking skills. Thus, technology-enhanced STEM-PjBL can serve as a relevant alternative approach for improving critical thinking skills, particularly in learning about the nature of science and scientific methods.

The implementation of technology-based STEM-PjBL provides opportunities for students to engage in more meaningful and authentic learning processes. In project-based activities, students are required to investigate real-world problems, identify variables, formulate solutions, and develop products that can be scientifically tested [5]. This process aligns with the characteristics of critical thinking, which emphasize analyzing information, evaluating arguments, and making evidence-based decisions [64]-[66]. Through the integration of technology, students can conduct digital explorations that enrich their learning experiences for instance, using simulations to understand abstract phenomena or digital applications to visualize experimental data. Such practices help create a learning environment that stimulates higher cognitive engagement compared to conventional instruction.

The STEM-PjBL model also inherently requires students to work systematically through stages of scientific inquiry. In completing their projects, students must integrate concepts from science, technology, engineering design, and mathematics to address the given problems comprehensively. These stages not only strengthen conceptual understanding but also reinforce students' ability to assess information quality, examine cause-and-effect relationships, and formulate logical solutions. Consequently, this approach directly supports the development of critical thinking skills, which is a central goal of 21st-century learning.

Moreover, the use of technology media in instruction provides additional benefits, including increased access to information, enhanced conceptual visualization, and greater ease in data validation. Technology enables students to conduct measurements, perform virtual experiments, or analyze graphs more efficiently and accurately, allowing instructional time to be redirected toward deepening scientific reasoning processes [67], [68]. This is consistent with constructivist theory, which posits that learning experiences built through active interaction with the environment including digital environments lead to stronger and more meaningful understanding [69], [70]. Thus, technology functions not merely as a tool but also as a catalyst that accelerates and facilitates critical thinking processes.

In addition to cognitive aspects, project-based learning encourages students to collaborate, communicate, and justify their reasoning to peers or teachers [71], [72]. Group discussions and project presentations offer opportunities for students to test arguments, defend their viewpoints, and evaluate the ideas of others. Such interactions play an important role in developing critical thinking skills, as students learn to interpret diverse perspectives and assess the strength of evidence used by their peers. Therefore, this approach contributes not only to individual skill development but also to collaborative competence, which further strengthens higher-order thinking skills.

Overall, technology-integrated STEM-PjBL is an instructional approach well aligned with contemporary educational challenges. By combining project-based problem solving with the use of digital technologies, this approach significantly enhances the quality of students' thinking processes [73]-[75]. In the context of learning about the nature of science and scientific methods, it provides students with opportunities to understand how scientific processes operate in real-world contexts and how technology can support data-driven decision-making. Accordingly, this approach can be considered an effective instructional strategy for improving critical thinking skills in science education.

3.4. Interview Results

The interview results are presented in Table 6 to provide qualitative insights into students' learning experiences during the project implementation. The findings highlight key themes related to student involvement in critical thinking activities, as reflected in the informants' statements and the researchers' interpretations.

Table 6. Interview Results

Main Theme	Informant Quotes	Researcher's Interpretation
Student involvement in critical thinking activities	"During the project, I asked more questions because I had to really understand the steps."	Students demonstrated increased engagement and critical questioning skills throughout the project process.
	"We often discussed the process to determine the most appropriate way to complete the task."	Students engaged in analysis and strategy selection, indicating improved evaluative skills.
The role of technology media in assisting data analysis	"The graphs from the application helped me clearly see the differences in experimental results."	Technology aided students in visualizing data and enhancing their interpretation skills.
	"The experiments felt easier because there were simulations, so I wasn't confused anymore."	Technology clarified experimental procedures, enabling a more effective understanding of the scientific method.

Improved self-reflection and evaluation skills	"I had to double-check that my data was correct before drawing conclusions." "If the results were different, I tried to find out what was wrong with the steps."	Students began to reflect and independently verify the data. Students conducted process evaluations, demonstrating advanced critical thinking skills.
Student responses to learning models	"Learning was more fun because I could try things out directly, not just listen to explanations." "I'm usually shy about speaking up, but this project made me more confident because we had to work in a group."	Project-based learning provided an active and enjoyable learning experience. The learning model fostered student participation.
Obstacles faced in learning	"It was a bit difficult to use the graphing application at first, but I got used to it." "The project was fun, but I felt like there wasn't enough time, so I had to work quickly."	Technical challenges emerged, but these were overcome through practice. Time management was a challenge in project implementation.

The interview results indicate that the STEM-PjBL learning model integrated with technological media provides students with more meaningful learning experiences. Most informants reported increased engagement throughout the learning process, particularly through group discussions, problem exploration, and collaborative decision-making. These findings suggest that project-based learning fosters strong collaborative dynamics, consistent with the core characteristics of STEM-PjBL, which positions students as central agents in developing solutions to real-world problems. This active engagement serves as an important factor contributing to the development of students' critical thinking skills.

In addition, the interviews reveal that students' critical thinking skills develop through the analytical and reflective processes carried out during project work. Informants stated that they learned to re-examine data, identify errors, and independently evaluate experimental procedures. These reflective activities demonstrate strengthened higher-order critical thinking components, such as evaluation, analysis, and metacognition. When students are prompted to revisit their data and connect it with the conclusions they draw, a reinforcement of scientific reasoning occurs aligning with the demands of the nature of science and scientific methods.

The integration of technological media also provides significant support for students' understanding and data analysis processes [76]-[78]. Many students expressed that using graphing applications, simulations, and digital tools helped them visualize experimental results and comprehend relationships between variables more easily [79]-[81]. Technology serves not only as an assistive tool but also as cognitive scaffolding that enables more accurate data interpretation [82], [83]. This finding is consistent with literature suggesting that technology plays a crucial role in enhancing critical thinking through more effective visualization and representation of data.

Alongside its benefits, the interviews also highlight several challenges faced by students, such as initial difficulties in using data analysis applications and limited time to complete the projects. Nevertheless, students noted that these challenges could be addressed through practice and guidance, and did not diminish the positive learning experiences they gained. This indicates that implementing the STEM-PjBL model with technological media requires careful time management and adequate technical support to optimize learning outcomes.

Overall, the qualitative findings from the interviews support the quantitative results, which demonstrate improvements in students' critical thinking skills. The interviews provide an in-depth understanding of how students experience the learning process, including the internal mechanisms that drive the development of critical thinking. Thus, the combination of STEM-PjBL and technology offers a pedagogically relevant approach for improving the quality of science learning, particularly in areas related to the nature of science and scientific methods.

These findings align with previous studies that show STEM approaches and project-based learning can enhance higher-order thinking skills, including critical thinking. The study by Fitriani et al. [84] demonstrates that project-based STEM learning provides students with opportunities to identify problems and construct solutions through systematic scientific reasoning, positively influencing the development of critical thinking. Another study by Kashaka [85], reports that technology integration in science learning helps students visualize concepts, test hypotheses, and analyze data more accurately. Additionally, findings from Wulandari et al. [86], show that technology-enriched learning environments can increase students' cognitive engagement in complex problem-solving activities. The consistency of these findings with prior research reinforces the argument that combining STEM-PjBL with technology is not only relevant but also effective in improving critical thinking skills, particularly in content areas requiring an understanding of scientific processes.

The implementation of technology-based STEM-PjBL in this study has positive impacts not only on strengthening critical thinking skills but also on increasing students' motivation and engagement throughout the learning process. Students appeared more active in exploring phenomena, participating in discussions, and constructing scientific project-based solutions. The use of technological media also assisted teachers in presenting abstract material in ways that are more concrete and engaging. Another impact is the creation of a collaborative learning environment that encourages students to think more reflectively and analytically. However, this study does have certain limitations. First, the relatively short duration of the intervention restricts the observation of long-term development of critical thinking skills. Second, teachers' abilities and readiness to use technology significantly influence the effectiveness of the learning model, meaning results may vary across different school contexts with differing facilities or teacher competencies. Third, the use of only two classes in the quasi-experimental design may introduce uncontrolled bias, even though a pretest was administered to equalize initial abilities. These limitations open opportunities for future research with a larger scale and stronger design to ensure broader generalizability of the findings.

4. CONCLUSION

This study concludes that the implementation of STEM-PjBL learning integrated with technological media has a significant impact on enhancing students' critical thinking skills in the topics of the nature of science and scientific methods. Project-based learning combined with digital technology support is able to create learning experiences that are more contextual, interactive, and cognitively challenging. Students are not only given opportunities to construct understanding through problem-solving activities but also develop analytical skills in evaluating data and formulating scientific solutions. The integration of technology assists in visualizing abstract phenomena and facilitates a more authentic scientific investigation process. Therefore, this learning model can serve as an effective alternative for improving higher-order thinking skills in science education, particularly in content areas that emphasize scientific processes. Future research is recommended to expand the sample size and involve more schools to strengthen the generalizability of the findings.

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USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried **out** entirely by the authors without the assistance of AI-based technologies.

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