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The Influence of Project-Based Learning Integrated with Science, Technology, Engineering, and Mathematics (PjBL-STEM) on Students' Critical Thinking Skills in Biology Education

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ABSTRACT

Project-Based Learning model integrated with Science, Technology, Engineering, and Mathematics (PjBL-STEM) is an innovative learning model that involves project work in which students independently construct their learning and accumulate it into tangible products. This study aims to measure the impact of the PjBL-STEM model on the critical thinking skills of 10th-grade students at MA Sumber Bungur Pakong, Pamekasan. The research method used is a quasi-experimental design with a Nonrandomized Control-Group Pretest-Posttest design. The research sample consisted of 47 students selected using random sampling techniques, divided into experimental and control groups. Data were collected through essay tests and questionnaires, and then analyzed using ANCOVA. The results indicate that the PjBL-STEM model has a significant effect on improving students' critical thinking skills. These findings suggest that PjBL-STEM is effective in developing critical thinking skills among students.

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1. INTRODUCTION

The rapid development of technology and social transformation has brought the world into the Society 5.0 Era, where digital technology is integrated into various aspects of life, drastically changing the job landscape. To prepare the younger generation for future challenges, adjustments in the education curriculum are essential. The 21st century requires 4C skills: Critical Thinking, Communication, Collaboration, and Creativity. Among these, critical thinking is crucial as it enables individuals to analyze information, solve problems, and make informed decisions. These skills are not just an added value but are at the core of the abilities needed to address the complex challenges of the future(Baran *et al.*, 2021). These skills are not just an added value but are at the core of the abilities required to address the complex challenges of the future.

Critical thinking is one of the essential skills that every individual in the 21st century must master. Critical thinking skills involve reflective, logical, and systematic thinking in analyzing information or problems to make valid decisions in problem-solving (Dwyer *et al.*, 2014; Syarifah *et al.*, 2018). The importance of developing students' critical thinking skills in the learning process has become a primary goal of education. Education is seen as a means to prepare students to engage in the workforce with analytical thinking, problem-solving, and critical thinking skills. This enables them to become productive workers, exchange information, and contribute to societal development and welfare (Sasson *et al.*, 2018). However, in reality, the learning process often does not encourage the development of critical thinking skills, as education is still teacher-centered, leaving students with limited opportunities to express their opinions (Saputra *et al.*, 2019). This is supported by the latest PISA results 2022, which show that many students struggle with critical thinking. For example, Indonesia scored 371 in reading, 379 in mathematics, and 396 in science, all of which are below the OECD average and indicate challenges in critical thinking. Notably, only 1% of Indonesian students achieved the highest proficiency levels in problem-solving, compared to the OECD average of 9% (OCDE, 2023). This highlights a significant gap in critical thinking abilities among students. These findings underscore the urgent need to shift from teacher-centered approaches to more student-centered learning methods that foster critical thinking. Learning tends to focus on memorization and information accumulation, which results in students understanding concepts theoretically but not being able to apply them practically, thereby hindering the development of critical thinking skills (Al-mahrooqi & Denman, 2020; Leonard & Amanah, 2017; Supena *et al*., 2021). Therefore, there is a need for a shift in teaching approaches that can effectively foster the development of students' critical thinking skills.

In response to the Society 5.0 era, where 21st-century skills such as critical thinking are increasingly important, education must introduce appropriate learning models. One prominent model is Project-Based Learning (PjBL), which encourages students to develop practical skills through exploration and projects (Solihin, 2021), and also emphasizes the integration of Science, Technology, Engineering, and Mathematics (STEM) to meet the demands of the times. The connection between science and technology, or other fields, is inseparable in science education (Isro *et al*., 2021). Product engineering in STEM education is closely related to project creation in PjBL (Parno *et al*., 2020). By integrating STEM into PjBL, a process is initiated that allows students to actively participate, solve problems, and pose questions related to their new experiences, enabling them to reflect critically on their ideas (Bulu & Tanggur, 2021). Through PjBL-STEM, students are encouraged to improve their analytical skills in addressing complex problems. This is important because critical thinking is a foundational skill for facing future challenges, where students need to adapt to rapid changes and solve problems with innovative and effective approaches. Therefore, PjBL-STEM becomes an effective tool for equipping students with relevant and necessary skills in the Society 5.0 era.

One of the topics in Biology at the high school/MA level that supports the development of students' critical thinking skills is environmental change, including the factors and impacts of environmental changes, as well as efforts to address them. Environmental issues, especially related to waste, have become global problems that must be tackled immediately. The lack of awareness and concern among the surrounding community is also a crucial factor in environmental change. This behavior needs to be addressed to resolve environmental problems effectively. Therefore, it is important for students to have critical thinking skills to solve local environmental problems. This research is significant to examine the effect of the Project-Based Learning model integrated with Science, Technology, Engineering, and Mathematics (PjBL-STEM) on the development of critical thinking skills in 10th-grade students in Biology learning at MA Sumber Bungur Pakong Pamekasan.

2. RESEARCH METHOD

This study employs an experimental research design with a quantitative approach. The type of research used is Quasi-Experimental. The specific Quasi-Experimental design applied in this study is the Nonrandomized Control-Group Pretest-Posttest Design (Leedy & Ormrod, 2021), The research was conducted from July to August 2024 with students in the tenth grade at MA Sumber Bungur Pakong in Pamekasan. The sample consisted of two classes. Random sampling techniques were used to determine the experimental and control groups, resulting in class X-B being selected as the experimental group with 24 students, and class X-E as the control group with 23 students. The total sample size for the study was 47 students. The test instruments used were validated and reliability tested, yielding valid and reliable results. Data collection techniques involved pretest and posttest scores for critical thinking skills, which were analyzed using One Way ANCOVA at a significance level of 5%. The study consists of two groups: the experimental group, which received treatment through the Project-Based Learning Integrated with Science, Technology, Engineering, and Mathematics (PjBL-STEM) model, and the control group, which received treatment through the Discovery Learning model, focusing on environmental change topics.

Tabel 1. Reseacrh Design

Group	Pretest	Treatment	Posttest
Experimental	O_1	X_1	O_2
Control	O_3	X_2	O_4

Sumber: Leedy & Ormod (2021:233)

Description

O_1 : Pretest for the experimental group
O_2 : Posttest for the experimental group
X_1 : Treatment for the experimental group using the PjBL integrated with STEM model
X2 : Treatment for the control group using the Discovery Learning model
O3 : Pretest for the control group
O4 : Posttest for the control group

3. RESULT AND DISCUSSION

The normality test for students' critical thinking skills was conducted using the Shapiro-Wilk test. The results of the normality test based on Table 2 for the experimental class critical thinking skills variable show that the pretest had a significance value of 0.181 > 0.05 and the posttest had a significance value of 0.098 > 0.05, indicating that the pretest and posttest data for critical thinking skills in the experimental class are normally distributed. For the control class critical thinking skills, the pretest had a significance value of 0.098 > 0.05 and the posttest had a significance value of 0.066 > 0.05, indicating that the pretest and posttest data for critical thinking skills in the control class are also normally distributed.

Table 2. Results of Normality Test using Shapiro-Wilk

Variable	Class	*Pretest*		*Posttest*	
		Significance	Data Distribution	Significance	Data Distribution
Critical Thinking Skills	Experimental (X-B)	0,181	Normal	0,098	Normal
	Control (X-E)	0,098	Normal	0,066	Normal

The results of the homogeneity test based on Table 3 show that the significance value for critical thinking skills is 0.807 > 0.05. This indicates that the pretest and posttest data for critical thinking skills in both the experimental and control classes are homogeneous. Therefore, the results of the homogeneity test show that the critical thinking skills data between the experimental and control classes are homogeneous.

Table 3. Results of Homogeneity Test using Levene's Test

Variable	Significance	Data Distribution
Critical Thinking Skills	0,807	Homogen

The research data, measured based on the dependent variable, in this case, critical thinking skills, were then analyzed using a One-Way ANCOVA test with the assistance of SPSS 16 for Windows. The data analysis results in Table 4 show a significance value of p = 0.000, which means the research hypothesis is accepted because p < α (0.05). This indicates a significant difference in critical thinking skills between the experimental class (PjBL-STEM) and the control class (Discovery Learning). The statistical test results, corrected means, and the Least Significant Difference (LSD) post hoc test can be seen in Table 5, which indicates that the PjBL-STEM learning model has a positive effect on students' critical thinking skills.

Table 4. ANCOVA Results for the PjBL-STEM Model on Students' Critical Thinking Skills

Tests of Between-Subjects Effects

Dependent Variable:*Posttest* KBK

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2665.486[a]	2	1332.743	380.986	.000	.945
Intercept	446.062	1	446.062	127.514	.000	.743
Pretest_KBK	1492.720	1	1492.720	426.718	.000	.907
Treatment	1179.977	1	1179.977	337.316	.000	.885
Error	153.918	44	3.498			
Total	344608.000	47				
Corrected Total	2819.404	46				

a. R Squared = ,945 (Adjusted R Squared = ,943)

The data in Table 5 indicate that the class using the PjBL-STEM model has an adjusted mean for critical thinking skills of 90.18, which is significantly different from the mean of the Discovery Learning class, which is 80.15. The results of the LSD post hoc test also indicate a significant difference between the two treatments, as evidenced by the different LSD notations.

Table 5. LSD Test Results on the Impact of Learning Models on Critical Thinking Skills

Learning Model	*Pretest*		*Posttest*		Difference	Improvement	Adjusted Mean	Notation
	M	(SD)	M	(SD)				
PjBL STEM	64.83	6.87	90.17	6.01	25.34	39.04%	90.18	a
Discovery Learning	64.87	6.71	80.17	6.08	15.30	23.56%	80.15	b

The advantages of the PjBL-STEM model in enhancing critical thinking skills can be seen from its more holistic and interactive approach. Students who learn through PjBL-STEM are directly involved in projects relevant to real-world environmental issues, which motivates them to think critically. This aligns with Baharin *et al*. (2018), who stated that the application of the PjBL model integrated with STEM provides students the opportunity to practice collaboration, problem-solving, critical thinking, creativity, and scientific thinking skills, all of which contribute to improving their higher-order thinking skills. In the experimental class using PjBL-STEM, students are given the opportunity to engage directly in challenging projects related to real-world environmental issues. The process involves five main stages: Reflection, Research, Discovery, Application, and Communication (Laboy-Rush, 2010). Each stage contributes to the development of students' critical thinking skills.

The first stage of the PjBL-STEM model is reflection, where students are encouraged to observe and record changes occurring in their surroundings related to waste issues. This activity involves the science aspect of the STEM approach, as it includes observations and real data recording, such as waste accumulation, odor description, and color changes in the environment. By noting these changes, students are trained to think analytically and critically about their environment. Group discussions held at this stage also enhance students' ability to express opinions and consider different perspectives. Besides encouraging students to observe real changes, this stage also aims to link their existing knowledge with new things they need to learn, thus enhancing their critical thinking skills. Arifin *et al*. (2024); Ningrum *et al*. (2024) explain that through reflection, students can sharpen their thinking skills by integrating prior knowledge with new understanding to solve problems.

The second stage of PjBL-STEM is research, which also contains the science aspect of the STEM approach. At this stage, students search for information about the causes and impacts of waste issues. Through data search, students learn to evaluate information sources, summarize findings, and present their results. This teaches them the importance of information validity and relevance, improving their critical thinking skills in assessing data. They gather data from various sources such as books or the internet. This process requires students to filter information and organize it into clear and informative summaries. This stage of finding and sorting information helps students analyze and identify the issues presented (Triprani *et al*., 2023).

The next stage is discovery, where students are required to conduct a thorough analysis of their research findings and design projects as solutions. This stage involves the engineering aspect of STEM because students focus on designing structured and planned solutions based on the information they have collected. By developing a project plan, students learn to make decisions based on gathered information while considering various aspects in the planning process. This process hones students' critical thinking skills in designing effective solutions and allows them to explore and integrate different ideas when seeking solutions. In line with this, Tipani (2019) states that this phase improves students' mastery of concepts and analytical thinking skills, which typically involves bridging the research phase and known information when designing a project.

The next stage in PjBL-STEM is application, which encompasses all aspects of STEM: Science, Technology, Engineering, and Mathematics. At this stage, students are given the opportunity to apply the solutions they have designed in real situations. They start by applying their scientific understanding of the impact of plastic and organic waste on the environment. In a project to create a plastic waste bin, students use scientific knowledge to understand the properties of waste that is difficult to decompose and its impact on ecosystems. Meanwhile, in managing organic waste, they apply their scientific knowledge of decomposition processes through composting, observing changes in the compost pile over time. An important aspect of composting is the use of local microorganisms (MOL), which help accelerate the decomposition process and improve the quality of the compost produced.

In terms of technology, students use tools to manage their projects. They can use measuring instruments to measure the plastic waste containers. This process also involves engineering aspects, where students design and build plastic waste containers and composting systems for organic waste. They go through planning, testing, and evaluation processes to ensure the solutions they create work effectively and efficiently, providing practical solutions to the waste issues at hand. Additionally, in applying mathematics, students calculate the volume of the plastic waste containers they design, as well as the ratio of materials used in the composting process. They also monitor and analyze changes in the compost pile using calculations related to decomposition speed and composting effectiveness. All these aspects work together to integrate theory and practice in a project that helps students understand the environmental impact of waste. This process provides students with the opportunity to evaluate the effectiveness of their solutions, make adjustments if necessary, and see the connection between the theory they learned and its application in real practice. This project impacts the enhancement of students' critical thinking skills because, in carrying out this project, students are required to implement the solutions they have previously designed. This experience also helps students evaluate the effectiveness of their solutions and make adjustments or improvements if needed. The process allows students to see the link between the theory learned and its application in practice. In line with this, Fitriyani *et al*. (2020) explain that at this stage, the evaluation process also takes place, where after the product is created, students test the results according to established criteria and then use those findings to improve or adjust previous steps.

The final stage of PjBL-STEM is communication, which also helps students develop critical thinking skills. In this stage, students present their project results to their classmates. Noviyanti (2011) states that structured student communication involves presenting opinions, discussing, and understanding issues. Here, students must prepare a clear and structured presentation and explain the impact and benefits of their projects. In this stage, there is an analysis and evaluation process to determine whether the product they have made is viable and to improve any shortcomings through discussion activities. In line with this, Fitriyah & Ramadani (2021) say that the evaluation process requires students to think critically when assessing both the positive and negative aspects of the project they created.

The implementation of PjBL-STEM in this study emphasizes the importance of student involvement in real-world projects relevant to their daily life context, where students are encouraged to explore environmental problems related to the management of plastic and organic waste, critical issues in society today. Afifah *et al*. (2019) in their research state that the PjBL-STEM model can improve students' critical thinking skills at a high level. The success of implementing the PjBL-STEM model in learning not only depends on the methodology applied but also on several key supporting factors. One of the main factors is time. Project-based learning requires sufficient time to plan, implement, and evaluate activities. Students need time to apply more complex solutions. Additionally, projects often require longer durations to complete, depending on how complex the proposed project is and the skill level of the students. Therefore, it is important for teachers to manage time effectively to maximize the output, not only for daily learning activities but also for completing the overall project so that students can explore the topic in depth and generate meaningful solutions.

Besides time, human resources (HR) also play a significant role in the success of PjBL-STEM. The teacher's ability to facilitate the project, provide guidance, and assess student progress is crucial. Teachers need to have project management skills and in-depth knowledge of the content being taught. Additionally, the number of available teachers can also influence the effectiveness of the project. According to Government Regulation Number 74 of 2008 on Teachers, Article 17, it is stated that for SD, SMP, and SMA levels, ideally, one teacher is responsible for 20 students (Wahyuningsih *et al*., 2021). Another important factor is costs and facilities. STEM-based projects often require specific tools and resources, such as materials for experiments, technology for research, or suitable classroom spaces for collaborative work, depending on whether the project is simple or more complex. The availability of proper facilities and adequate funding to support the project implementation activities is key for students to learn optimally.

4. CONCLUSION

This study demonstrates that the PjBL-STEM model significantly enhances students' critical thinking skills compared to the Discovery Learning model. Statistical analysis confirms that students in the experimental group experienced a greater improvement in critical thinking after the treatment. These findings suggest that a project-based learning approach integrated with STEM can be an effective strategy for developing critical thinking skills. Future research could explore its long-term impact and implementation across different subjects and educational levels.

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