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The Impact of a Problem-Based Learning Model Combined with a STEM Approach on the Critical Thinking Abilities of High School in Buffer Solution

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Abstract

STEM-based Problem-Based Learning (PBL) is a student-centered learning process designed to enhance critical thinking skills within the framework of 21st-century skillsThis research seeks to examine the differences in critical thinking and collaboration skills between students using STEM-integrated Problem-Based Learning and those engaged in Discovery Learning in the context of buffer solutions. The research subjects consisted of four classes (N=130) of students at SMAN 2 Muara Beliti. This study involved two treatment groups, with the experimental group utilizing the STEM-based Problem-Based Learning (PBL) model and the control group employing the Discovery Learning (DL) model. Critical thinking skills instruments were used as relevant data collection tools. The obtained data were analyzed using ANOVA. The results showed an effect of the PBL model on critical thinking skills, evidenced by a significance value of <0.05. Considering these average scores, there is a difference between students participating in PBL and those participating in DL. The use of the PBL model in the experimental class enhanced critical thinking skills more effectively compared to the control class. The result collected through discussion with literature review and suggestions provided. The STEM-integrated PBL approach is found to be more effective in boosting critical thinking skills compared to the DL model. The contribution of the STEM-integrated PBL to critical thinking skills is 14%, indicating a moderate level of effectiveness.

Keywords: Buffer Soution, Critical Thinking Ability, Chemistry Learning, Problem-Based Learning,STEM

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Introduction

Teaching is an activity that should effectively influence students' behavior and demonstrate the outcomes or impact of the learning process. For that reason, the teaching methods employed must be capable of stimulating students, offering them opportunities to enhance their cognitive abilities, particularly in higher-order thinking. Education today aims to teach students the process of asking questions, organizing, constructing, commenting, forming hypotheses and discovering facts on their own (Nisa, Koestiari, Habibbulloh, & Jatmiko, 2018).

The quality of education needs to be improved and can no longer be delayed in line with the demands of the 21st century faced by students. In Indonesia, 21st-century skills are categorized as low, especially critical thinking skills (D'Alessio, Avolio, & Charles, 2019; Fong, Kim, Davis, Hoang, & Kim, 2017; Veliz & Veliz-Campos, 2019). The 21st-century skills outlined in Learning and Innovation Skills consist of critical thinking, creativity, communication, and collaboration (Trilling & Fadel, 2012; Hidayati, Zubaidah, & Amnah, 2022). Critical thinking skills are the ability to reason in an organized manner in an effort to find solutions to problems faced, make decisions, and form beliefs accompanied by evidence. Critical thinking is the ability to find solutions to challenges encountered by students in learning scenario (Zubaidah, Corebima, Mahanal, & Mistinah, 2018; Bellaera, Weinstein-Jones, Ilie, & Baker, 2021). This skill is important and necessary for students to address real-life problems directly (Geisinger, 2016; Fitriani, Zubaidah, Susilo, & Al-Muhdhar, 2020).

Critical thinking skills encompass the capacity to analyze information, articulate ideas, defend viewpoints, make comparisons, draw conclusions, assess arguments, and solve problems (Pramestika, Wulandari, & Sujana, 2020; Rati & Rediani, 2020). Critical thinking refers to a person's cognitive ability to confidently assert a point, grounded in logical reasoning and solid evidence (Hyytinen, Nissinen, Ursin, Toom, & Lindblom-Ylanne, 2015) and is related to students' thinking. The ability to face everyday problems (Odebiyi & Odebiyi, 2021) it is strengthened by offering students opportunities to utilize information sources to develop solutions and establish connections (Polat & Aydin, 2020). Critical thinking skills are among the essential learning outcomes in the field of education (Hart, Da Costa, D'Souza, Kimpton, & Ljbusic, 2021; Yu, et al., 2021; Pramesti, Probosari, & Indriyanti, 2022), therefore, innovative teaching strategies are necessary to foster and develop students' critical thinking abilities (Seilbert, 2021; Silberman, Carpenter, takemoto, & Coyne, 2021).

Critical, creative, and independent thinking are also part of strengthening students' character in the independent curriculum and are important aspects in addressing the challenges of the 21st century (Silviariza, Sumarni, & Handoyo, 2021) Independence can be defined as the attitude and characteristics of students who learn, identify their own learning needs, have desired learning goals, are always enthusiastic, and evaluate what they have learned (Elmouhtarim, 2018) This requires students' skills to manage knowledge deeply, analyze, and assess problems. Therefore, STEM-based Problem-Based Learning (PBL) model is needed to enhance students' critical thinking skills. One method used to implement and improve the quality of learning outcomes is to apply a learning model that aligns with the material and the conditions of the students (Buchs & Butera, 2015). Problem-Based Learning (PBL) is a problem-based learning model used in the learning process. The problems used are real-life issues or the latest issues related to everyday life. PBL activities are carried out entirely by students but still under the guidance of the teacher as a facilitator (S. Barrows & M.Tamblyn, 1980).

STEM is an educational approach that has arisen in response to the growing societal demand for economic advancement and scientific research (Yilmaz, Gulgun, Cetinkaya, & Doganay, 2018). The main goals of STEM are to (1) develop a qualified workforce, (2) adopt STEM disciplines and gender equality, and (3) to ensure that individuals in society acquire 21st-century skills, it is essential to focus not only on critical and creative thinking but also on enhancing literacy across various domains, including the ability to argue effectively (Carnevale, Smith, & Melton, 2011; Memis & Cevik, 2018). Currently, STEM goals are introduced from an early age, including in middle schools, elementary schools, and even kindergartens. Integration is a key aspect that is carefully planned for implementation within the STEM educational approach (DeChenne, Koziol, Needham, & Enochs, 2017; Torres & Cristancho, 2018; Gullen & Yaman, 2019).

PBL (Problem-Based Learning) with a STEM (Science, Technology, Engineering, and Mathematics) approach is a student-centered learning process aimed at enhancing critical thinking skills, which are essential in the 21st century. This learning process serves as a good alternative for improving students' understanding and presents a challenge for them (Dervic, Glamocic, Gazibegovic-Busuladzic, & Mesic, 2018; Erdogan, Navruz, Younes, & Capraro, 2016; Tudu, Ali, & Ahmad, 2023). It has the competence to improve academic achievement. The approach involves hands-on activities, active student participation, collaboration for problem-solving, communicating results, and assessing findings, all of which are related to real-life situations. Students are required to master technological advancements and scientific knowledge. The learning approach that can be used to meet this challenge is STEM (Science, Technology, Engineering, and Mathematics) (Akpan & Kennedy, 2020). STEM education is highly effective as it trains students to integrate multiple aspects in their learning. This approach helps in forming knowledge from various perspectives and comprehensively (Song, 2020; Martinez-Borreguero, Naranjo-Correa, & Mateos-Nunez, 2022).

Students face difficulties in learning chemistry because the material taught does not feel relevant to everyday life and because the complexity of chemistry content is very high. This results in a lack of interest and active engagement from students in the learning process (Magwilang, 2016). Buffer solutions are one of the topics studied by high school students. The concept of buffer solutions is abstract, making it difficult for students to understand the material during lessons (Onen & Ulusoy, 2014). This aligns with the opinion of (Marsita, Priatmoko, & Kusuma, 2010), who state that there are several areas of difficulty for students in understanding this material, including: difficulty in understanding the concept of buffer solutions at 35.52%; the concept of calculating pH and pOH of buffer solutions using equilibrium principles at 26.03%; the concept of calculating the pH of buffer solutions when adding small amounts of acid or base at 40.83%; and the concept of the function of buffer solutions in living organisms and in everyday life at 68.26%.

Previous research indicates that several studies have investigated students' academic performance and attitudes toward STEM concurrently. However, there seems to be a gap in empirical research specifically assessing the impact of STEM PBL on students' academic achievement alone. Various studies suggest that STEM PBL has a notable effect on students' cognitive development during problem-solving tasks (Han, Rosli, Capraro, & Capraro, 2016). Meaningful and fulfilling learning takes place when students engage actively and collaboratively in solving real-world problems, which ultimately impacts their academic performance (Barron, et al., 1998). Similarly (Lou, Liu, Shih, Chuang, & Tseng, 2011) discovered that the chosen students in their study not only acquired deep knowledge in science and mathematics but were also able to apply engineering and scientific knowledge during exploratory activities. Similarly, (Marino, Black, Hayes, & Beecher, 2010) It was noted that students with reading difficulties exhibited notable differences in STEM achievement after engaging in technology-enhanced learning, although their academic performance was affected by various factors. This highlights a consistent correlation between elements such as STEM curricular materials integrated with technology, which positively impact the performance of students with disabilities in STEM. This study aims to compare critical thinking and collaboration skills between students using STEM-integrated Problem-Based Learning and those following Discovery Learning in the context of buffer solutions. Consequently, the study focuses on evaluating the impact of the PBL model with a STEM approach on critical thinking skills and seeks to address the following research questions.

- What impact does the PBL learning model with a STEM approach have on students' critical thinking skills?
- What category of effective contribution does the STEM-supported PBL learning model make to students' critical thinking skills?

Methodology

Research Design

This study employs a quantitative method with a quasi-experimental design using a post-test only with control group (Rogers & Revesz, 2019). Research involves experimental and control classes, comprising 2 experimental classes and 2 control classes. The experimental classes are subjected to the integrated PBL with STEM learning model, while the control classes are subjected to Discovery Learning (DL) model. Table 1 shows learning stages of experimental class with PBL-STEM model treatment and control class with DL model treatment

Table 1.

Comparison of Syntax of PBL-STEM and DL Learning models

	Experiment Class	Control Class
SYNTAX	**Introduction** • Apperception • Learning objectives **Core activities** • Student orientation to problems (aspects of competence, science (S) and Technology (T)) • Organizing students to learn (Mathematics (M) aspect) • Assist student and group investigations (Mathematics (M), Engineering (E) and Technology (T) aspects) • Develop and present work • Analyze and evaluate the problem solving process (Engineering aspect) **Closing** • Conclusion • Notification of the next learning material	**Introduction** • Apperception • Learning objectives **Core activities** • Stimulation • Problem Statement • Data collection • Data Processing • Verification • Generalitation **Closing** • Conclusion • Notification of the next learning material

Sample

The population for this study consists of all 11th grade science students at SMAN at Musi Rawas for the academic year 2023/2024. Random sampling was used as the sampling technique. The total sample size is 130 students, comprising 65 students in the experimental group and 65 students in the control group. The research was conducted at SMAN 2 Muara Beliti

Data Collection Instrument

The research instrument used in this study is a critical thinking skills test consisting of 10 essay questions. These questions are designed based on the critical thinking specifications proposed by Ennis (1991) which include elementary clarification, basic support, inference, advanced clarification, strategies and tactics. Aspects used in critical thinking skills and indicators used in critical thinking skills aspects are given in Table 2.

Table 2.
Indicators of Critical Thinking Ability

Aspect	Question Indicators
elementary clarification	Students are presented with weak acid and salt solutions and identify the components and species that affect the properties of these solutions.
	A description of a carbonated drink is presented, then, students are asked to calculate the pH of the solution mixture.
	Presented one example of a basic buffer solution, then students provide reasons for the compound to be included in the basic buffer solution.
	Presented one example of a buffer solution, namely blood, then students mention the reasons for blood as a buffer solution.
basic support	Presented with a description related to the making of buffer solution, then students mention and explain how to make buffer solution.
İnference	Presented with a description of buffer solution related to alkalosis, then learners analyze some facts related to buffer solution.
	Presented a discourse related to the buffer in the cell, then students analyze the changes in pH in the blood if excessive.
	Presented with a discourse on the function of buffer solutions in the pharmaceutical field, learners analyze why injectable drugs and eye drops meet the properties of buffers.
advanced clarification	Presented a discourse of buffer solutions with several volumes, then students identify the solution system and how to identify buffer solutions.
strategies and tactics	Presented some buffer solutions, then students analyze and make the buffer solution.

The use of cognitive ability tests serves to measure critical thinking skills. Before being tested on students, the critical thinking skills instrument was tested for validity and reliability. Validation is done theoretically and empirically. Theoretical validation was carried out by a validator who was a material expert lecturer, while empirical validation was carried out by testing the test instrument outside the research sample (Creswell, 2011). Theoretical validity measures the extent to which the test instrument covers all the objects being measured. The instrument was evaluated by expert lecturers who served as validators. The correction results are taken into consideration for improvement and refinement of the instrument so that the instrument is considered suitable for use as a measuring tool. The test questions were then empirically validated.

Empirical validation was carried out outside the research sample. The outcomes of the item trials were analyzed using the Rasch model with the help of the Winstep program. The results of the empirical validity analysis included a good category so that 10 items were suitable for use. Therefore, it can be interpreted that the reliability of the critical thinking ability question instrument is reliable so that the instrument can be used in research.

Data Collection Instrument

Data were collected from the post-test results of critical thinking skills. The data were analyzed using a One-way Analysis of Variance (ANOVA) at a significance level of 0.05, with SPSS 27.0 software. The research involves experimental and control classes, comprising 2 experimental classes and 2 control classes. The experimental classes are subjected to the integrated PBL with STEM learning model, while the control classes are subjected to Discovery Learning (DL) model.

Findings

Analysis of Critical Thinking Skills and Collaboration Skills

The average score data of critical thinking skills and science process skills for the experimental and control classes include posttest data. The results obtained from the critical thinking skill scores of the experimental and control groups are given in Table 3. This table is presenting data based on experimental and control classes including students in each class, highest and lowest scores, and averages scores in each class

Table 3.
Result of Critical Thinking Skills Scores

Class	Number of Student	Average Score	Lowest Score	Highest Score
Experiment 1	33	73,53	60	90
Experiment 2	32	70,13	48	88
Control 1	32	62,53	40	85
Control 2	33	63,76	40	83

In the univariat analysis, no outliers were detected in the dependent variable results for each group. This was verified by examining the univariate scatter plot, as illustrated in Figure 1.

Figure 1.
Box Plot of Critical Thinking Skills in the Experimental and Control Classes.

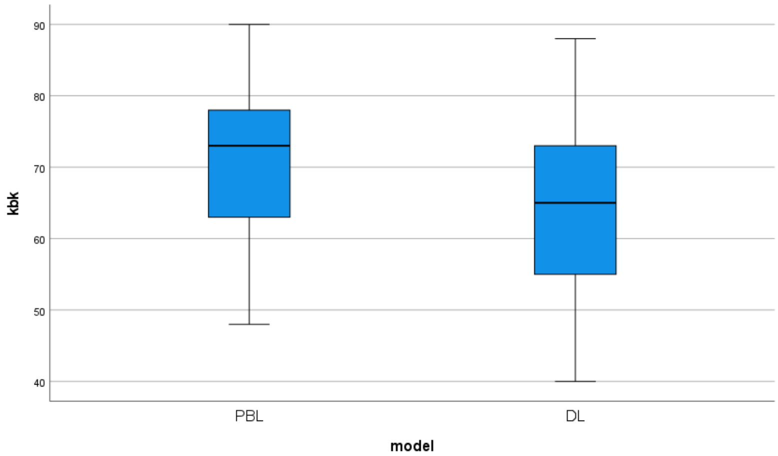

Figure 1 indicates that there are no univariate outliers in the critical thinking skills data for both the experimental and control classes, as evidenced by the absence of data points outside the box plot.

The Shapiro-Wilk test was employed to evaluate the univariate normality of the data distribution and the results are presented in Table 4.

Table 4.
Significance Values of Normality Test

Dependent Variabel	Class	*Shapiro Wilks*
Critical Thinking Skills	Experiment	0.267
	Control	0.170

According to the results in the Table 4, the results of critical thinking ability data analysis to see that the data is normal and can be used for ANOVA tests. For that reason H0 is accepted since all significanse values are greater than 0.05

To determine the differences between groups with different treatments, a one-way ANOVA test was conducted on critical thinking skills. The one-way ANOVA test data for each treatment group is provided in Tables 5 and 6.

Table 5.
Homogeneity of Variances Test

Instrument		Levene Statistic	df1	df2	Sig.
KBK	Based on Mean	.920	1	128	.339
Post-test	Based on Median	.787	1	128	.377
	Based on Median and with adjusted df	.787	1	124.348	.377
	Based on trimmed mean	.934	1	128	.336

Abberivations: df= Degree of Freedom, Sig.= Significance

Table 6.
One-Way Anova Test

Instrument		Sum of Squares	df	Mean Square	F	Sig.
KBK	Between Groups	2455.577	1	2455.577	20.108	0.000
post-test	Within Groups	15630.923	128	122.117		
	Total	18086.500	129			

Abberivations: df= Degree of Freedom, Sig.= Significance.

Discussion and Conclusion

The results of the study indicate that the PBL learning model significantly influences critical thinking skills. This is demonstrated by a significance value of less than 0.05, resulting in the rejection of H0. The experimental class had an average critical thinking skills score of 71.84, whereas the control class had an average score of 63.15. Based on these average scores, there is a noticeable difference between students who participated in PBL and those who followed DL. The use of the PBL model in the experimental class enhanced critical thinking skills more effectively compared to the control class.

Critical thinking skills are a measure for conducting basic clarification, evaluating the support of basic information, drawing conclusions, performing clarification, and applying strategies in problem-solving. In the activity of performing basic classification, which consists of statements and analyzing arguments, the indicators of student questions must be adjusted to the problem and its context. When analyzing arguments, students identify the reasons for the given arguments. Critical thinking is the ability to argue in an organized manner (Ennis R. , 2018).

Critical thinking involves giving opinions, listing facts, or providing reasons to support a decision (Cottrell, 2023). Critical thinking skills are high-level thinking abilities that are reflective, logical, analytical, interpretative, and self-regulative (Paul & Elder, 2007). Critical thinking is a thought process that results in conceptualization, analysis, synthesis, evaluation, observation, experience, and reasoning (Fisher, A., 2011; Philips, Chesnut, & Rospond, 2004). Similarly, (Seibert, 2021) states that critical thinking is the process of questioning, analyzing, synthesizing, interpreting, and applying reasoning and creativity.

The execution of the STEM-based PBL learning model was effectively carried out, in line with the findings of the study by (Mutakinati, Anwari, & Kumano, 2018) which reported that the STEM-based PBL learning model proved to be effective, achieving a score of 90% This result is also in line with the study by (Reynders, Lantz, Ruder, Stanford, & Cole, 2020), which indicated that the implementation of the learning process was highly effective, with a score of 3.6. This suggests that each stage of the learning process was executed proficiently. The STEM-based PBL learning model enables students to engage in learning activities such as analyzing problems, designing and creating tools, interpreting received information, and providing explanations (Soros, Ponkham, & Ekkapim, 2018). The learning process offers students new experiences and encompasses stages such as elaboration, cooperation, and collaborative interaction from start to finish (Bakirci & Kutlu, 2018)

The implementation of the STEM-based PBL model has a positive and effective impact on critical thinking skills. This result is consistent with the research by (Admiraal, et al., 2019; Chine & Larwin, 2022; Donohue, Buck, & Akerson, 2020), which states that the positive outcomes of applying the PBL learning model can enhance the critical thinking skills of high school students. The increase in students' critical thinking skills through STEM-based PBL learning received a positive response to the application of the STEM-based PBL model (Wan, Jiang, & Zhan, 2021; Wang, Chen, Hwang, Guan, & Wang, 2022). Learning with STEM encourages students to discuss and express ideas and thoughts to answer LKPD questions according to the learning steps. Students obtain observed information and describe new ideas by understanding experiments and answering questions according to their abilities and knowledge (Anesa & Ahda, 2021; Yang & Baldwin, 2020).

The research results indicate that PBL influences critical thinking skills. PBL aims to help students in problem-solving and developing thinking skills (Fadilla, et al., 2021; Chan, Gondhalekar, Choa, & Rashid, 2022). The main focus of PBL learning is to present authentic problems in learning. Students are not immediately given knowledge, but are required to discover knowledge independently in the application of everyday life. Activities such as analyzing problems, seeking solutions, determining solutions, and evaluating solutions in problem-solving provide students with habits for developing thinking skills.

This is in line with the research conducted by (Suhirman, Prayogi, & Asy'ari, 2021; Anggraeni, Prahani, Suprapto, Shofiyah, & Jatmiko, 2023), which found that the application of the PBL model better enhances students' critical thinking skills compared to conventional methods. The PBL learning model encourages students' critical thinking skills to provide solutions in multidisciplinary problem-solving, thus allowing students' understanding to last longer. Furthermore, according to (Santyasa, Santyadiputra, & Juniantari, 2019), the PBL learning model provides a learning process that enables students to acquire critical thinking skills, problem-solving skills, and creative thinking.

In line with the research conducted by (Suryanti & Nurhuda, 2021; Wahyu, Suastra , Sadia, & Suarni, 2020), it is explained that the learning process based on the syntax of the PBL model includes activities such as presenting the results of problem-solving, which involves a question-and-answer session guiding students to master the material being studied. Students gather information from books, engage in discussions, and share the information with other group members so that all groups achieve the same understanding. This approach enables students to collaboratively develop problem-solving skills to generate accurate solutions.

The PBL learning process involves small groups engaging in investigative or inquiry activities with the teacher acting as a facilitator. The subsequent activity includes presenting the investigation results to the group and analyzing and evaluating the problem-solving outcomes. These activities are conducted in small groups, where students discuss, provide solutions, and assess the solutions offered. These activities support the growth of critical thinking skills among students. Problem-Based Learning (PBL) is particularly effective in fostering critical thinking because it requires students to actively engage in problem-solving (Eldy & Sulaiman, 2013).

Based on the results of research conducted and supported by other studies, it can be concluded that the steps of the problem-based learning model have an impact on students' critical thinking. The problem-based learning model is suitable for application in the chemistry learning process, which requires analysis and critical thinking skills

Conclusion

The analysis and discussion reveal a significant difference in critical thinking skills between students who experienced STEM-integrated PBL and those who followed Discovery Learning (DL) on the topic of salt hydrolysis. The STEM-integrated PBL approach is found to be more effective in boosting critical thinking skills compared to the DL model. The contribution of the STEM-integrated PBL to critical thinking skills is 14%, indicating a moderate level of effectiveness.

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