Jurnal Pendidikan Kimia (JPKIM)
p-ISSN: 2085-3653| e-ISSN: 2549-3116
https://jurnal.unimed.ac.id/2012/index.php/jpk/index

OPEN ACCESS
10.24114/jpkim.v16i3.65189
J. Pendidik. Kim 2024, 16(3), 257– 262

Original Research Article

The differentiated STEM approach in problem-based learning: Can it enhance students' critical thinking skills in basic chemistry laws

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Citation: Majid, K., Mulyani, S., Ulfa, M., & Shidiq, A.S. (2024). The differentiated STEM approach in problem-based learning: Can it enhance students' critical thinking skills in basic chemistry laws. Jurnal Pendidikan Kimia (JPKIM), 16(3), 257 – 262. https://doi.org/10.24114/jpkim.v16i3.65189

ARTICLE INFO

Keywords:
Basic chemistry law;
Critical-thinking skill;
Differentiated;
Problem-based learning;
STEM

History:
♦Received - 25 Nov 2024
♦Revised - 26 Dec 2024
♦Accepted - 28 Dec 2024

ABSTRACT

The 21st century highlights the critical role of education in developing life skills, including critical thinking, to address rapid global changes. The learning process in schools becomes a critical factor in strengthening these skills. Therefore, this study aims to determine the effect of the Differentiated Problem-Based Learning (PBL) model with the STEM approach on students' critical thinking skills on basic chemical laws in class X of a Senior High School in Surakarta. Samples were selected using cluster random sampling to choose two classes as samples, namely, the experimental and control classes. Research data was collected through a post-test using an essay measuring students' critical thinking skills. The results were analyzed using the Kruskal-Wallis's test based on the mean post-test scores of the experimental class (73.00) and the control class (64.4), yielding a significance value of 0.004 (< 0.05). These results indicate a positive effect of Differentiated PBL-STEM on students' critical thinking skills. Skilled group students consistently demonstrated critical thinking skills, while students in the intervention and intermediate groups showed improvements from the initial diagnostic results of the learning process.

Introduction

The 21st century is marked by openness and rapid globalization, bringing significant changes to various aspects of life (Wijaya et al., 2016). In this era, education has become an essential and inseparable process of human civilization to ensure life skills, abilities, knowledge, and character values (Rahmat, 2014; Wijaya et al., 2016; Niyarci et al., 2022). According to Article 3 of Law No.20 of 2003, the goal of national education is to develop competencies and shape the nation's character with dignity, fostering individuals who are faithful, pious, virtuous, knowledgeable, creative, independent, democratic, and responsible. 21st-century learning emphasizes student-centered approaches, enabling the development of essential skills (Selamat, 2021). The National Education Association (NEA) identifies four key 21st-century skills, known as "The 4Cs" which include critical thinking, creativity, communication, and collaboration.

Critical thinking skills are essential for supporting learning success. According to Ennis (2011), critical thinking is a reflective process focused on decision-making. Facione (2011) further elaborates that critical thinking involves judgment through a goal-oriented process that leads to understanding, analysis, evaluation, and conclusions based on strong evidence. An individual possesses critical thinking skills if they meet the indicators of interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 1990). These skills are crucial for decision-making, problem identification, and formulating creative solutions (Susilawati et al., 2020; Tang et al., 2020). However, the reality shows that Indonesian students' critical thinking skills remain low across all indicators, necessitating improvement efforts (Susilawati et al., 2020; Rammadan & Budiman, 2022). This is further supported by data from PISA 2018, which revealed a decline in scores for reading, mathematics, and science, placing Indonesia 72nd out of 78 countries (Wardani et al., 2022; Putri et al., 2023). Based on these findings, enhancing critical thinking skills is crucial for navigating complex problems and making informed decisions. Efforts to improve these skills can be achieved by implementing learning models such as problem-based learning (Fadiawati et al., 2020; Amini et al., 2021), project-based learning (Rahmawati et al., 2021), discovery learning (Mardiani et al., 2022), and inquiry learning (Rose et al., 2023).

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Based on the literature review, the Problem-Based Learning (PBL) model is effective in enhancing critical thinking skills in science education as it provides a relevant learning context and facilitates the development of understanding and constructive thinking through problem-solving processes (As-Sa'idah et al., 2022). The implementation of PBL can be integrated with other approaches that also promote critical thinking skills, such as the STEM approach, which combines the interdisciplinary fields of science, technology, engineering, and mathematics (Han et al., 2016). The STEM approach stimulates higher-order thinking, motivates independent learning, and improves 21st-century skills, including critical thinking (Chen & Lin, 2019; Parno et al., 2021).

Integrating the Problem-Based Learning (PBL) model with the STEM approach can significantly enhance critical thinking skills (Ariyatun & Octavianelis, 2020). Through the process of understanding problems and designing solutions (Fadhilah et al., 2022; Herman et al., 2023) in science education, particularly in chemistry, which is closely related to real-life applications and involves abstract, conceptual, and complex materials, so critical thinking becomes essential (Syahri et al., 2017). One of the chemistry topics that requires critical thinking is the fundamental laws of chemistry, which are foundational concepts underpinning calculations in chemistry. Research findings indicate that applying the PBL model to the topic of the fundamental laws of chemistry can improve critical thinking skills and academic performance (Emelda et al., 2019; Sabora et al., 2022).

Student-centred learning naturally requires more creative and flexible learning concepts, which can be designed using approaches such as Teaching at the Right Level (TaRL) of differentiation (Basir et al., 2023). Differentiated learning engages students responsively and proactively, as it aims to meet the needs of each individual, acknowledging the diversity and dynamic nature of students (Purnawanto, 2023), so that it can support the improvement of students' critical thinking skills (Avandra & Desyandri, 2022). Research on Problem-Based Learning (PBL) integrated with the STEM approach to enhance critical thinking skills has been widely conducted. However, studies that combine these approaches with differentiated learning are still scarce. Therefore, this study focuses on the effect of the differentiated STEM approach in Problem-Based Learning on students' critical thinking skills in the topic of the fundamental laws of chemistry in Grade X.

Methods

Sample and Population

The sample consisted of two normal and homogeneous Grade X classes selected from the population of Grade X students at a public high school in Surakarta, Central Java.

General Procedure

The quantitative study used a quasi-experimental method with a posttest-only nonequivalent control group design. Sample selection was carried out using cluster random sampling for two research classes; the experimental class, which implemented a differentiated STEM approach with Problem-Based Learning model, and the control class, which utilized the Problem-Based Learning model. The data collection of 10 essay questions with a content validity (CV) of 1 and a reliability of 0.95, categorized as highly valid and highly reliable.

Data Analysis

The posttest result were analyzed using SPSS with the Kruskal-Wallis test to examine the effect of the learning model on critical thinking skills in the experimental and control class.

Results and Discussion

In the experimental class, process differentiation was applied (Fig-1) by forming homogeneous discussion groups based on the results of a cognitive diagnostic test (Table 1). Based on Table 1, the experimental class showed a diagnostic tendency towards the proficient group, with a frequency of 15 students (50%), while the control class had only 11 students (36.67%). This indicates that students in the experimental class had a better initial understanding of the foundational concepts supporting basic chemistry laws.

Table 1. Distribution of cognitive diagnostic test scores

Group criteria	Experiment class		Control class	
	Frequency	%	Frequency	%
Intervention	4	13.33%	9	30.00%
Moderate	11	36.67%	10	33.33%
Proficient	15	50.00%	11	36.67%
Total	30			30

Table 2. Distribution of posttest scores on critical thinking skills

Critical thinking skill criteria	Experiment class		Control class	
	f	%	F	%
25-42 (Low)	1	3.33%	2	6.67%
44-62 (Moderate)	4	13.33%	7	23.33%
63-81 (High)	17	56.67%	21	70.00%
82-100 (Very High)	8	26.67%	0	0.00%
Total	30		30	

Afterward, at the end of the learning process, a posttest was administered to both the experimental and control classes. The posttest results were used to assess students' critical thinking skills. The posttest results are presented in Table 2. In the experimental class, with the PBL-STEM-differentiated learning model, 17 students reached the high category with posttest critical thinking scores ranging from 63 to 81. Eight students achieved the very high category with scores between 82 and 100. There were also 4 students in the moderate category with scores ranging from 44 to 62, and 1 student in the low category with a score between 25 and 43. These results show that many students in the experimental class achieved high to very high levels of critical thinking skills after the learning process.

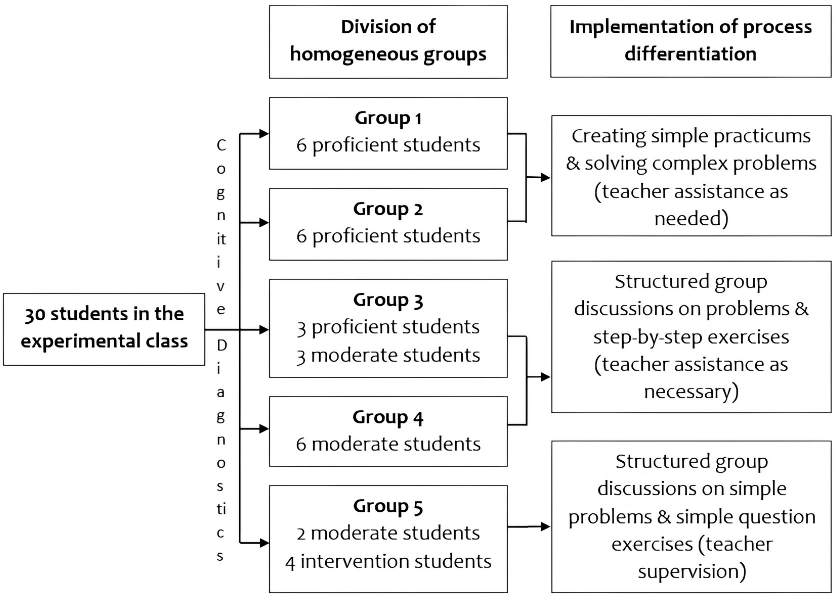

Fig-1. Process differentiation group

Meanwhile, in the control class with the PBL learning model, 21 students achieved the high category, 7 students were in the moderate category, and 2 students were in the low category. These results indicate that most students in the control class had high critical thinking skills, although the experimental class showed a tendency for higher outcomes.

This is supported by the average posttest score calculation for both the experimental and control classes, which shows that the experimental class had a higher-class average compared to the control class (Fig-2).

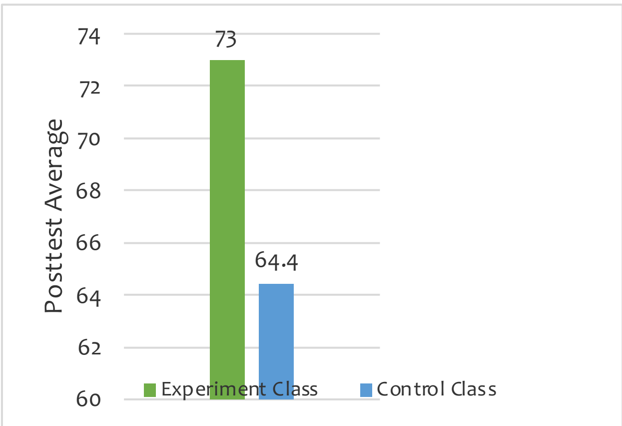

Fig-2. Average posttest critical thinking skills scores

The average posttest score for the experimental class (73.00) was higher than that of the control class (64.4). This aligns with the initial diagnostic results, where 50% of the students in the experimental class were categorized as proficient. These findings indicate a positive correlation between the initial diagnostic results and the critical thinking skills of students after receiving the PBL-STEM-differentiated learning. This learning model involved collaboration and group discussions, organized based on students' abilities, which helped improve the skills of students in the intervention and moderate categories. On the other hand, proficient students demonstrated consistency in their high skill levels.

The research results show that the average score for the proficient group is above the class average, the moderate group has an average that is not far from the class average, while the intervention group has an average that is significantly lower than the class average. These results can be seen in Table 3.

This result aligns with Jean Piaget's learning theory, which suggests that children can learn naturally through interaction and experience with their environment. In the experimental class with PBL-STEM-Differentiated learning, students actively participated and engaged in problem-solving according to their abilities and groups. This is in line with Vygotsky's learning theory, which posits that students can develop their skills through social interaction and tasks tailored to their abilities (Rohmah, 2021).

Tabel 3. Average posttest scores for each group

Group	Average	Critical thinking skill criteria
Group 1 (Proficient)	86.50	Very High
Group 2 (Proficient)	77.33	High
Group 3 (Moderate)	73.33	High
Group 4 (Moderate)	70.00	High
Group 5 (Intervention)	57.67	Moderate

The findings are also supported by data showing that the critical thinking skills achievement in the experimental class was higher than in the control class (74.67% > 64.69%), as well as the Kruskal-Wallis test results, which indicated a significance level of less than 0.05 (0.004 < 0.05), meaning there is an impact of the PBL-STEM-Differentiated learning model on students' critical thinking skills. This can be attributed to the fact that students in the experimental class demonstrated superior skills in analyzing problems in the questions, allowing them to provide answers with relevant explanations. Furthermore, students in the experimental class were more accustomed to concrete and real-life problems compared to the control class. This is because, in the learning process, the experimental class was given worksheets containing real and complex problems, encouraging them to understand the issues and provide appropriate solutions independently, without full teacher assistance. They were also supported by simple practical projects that helped enhance their conceptual understanding in line with the STEM approach.

This finding is consistent with several studies showing that the PBL-STEM learning model can improve critical thinking skills according to the stages of learning, supported by the STEM process (Satriani, 2017; Rizkihati et al., 2019). STEM helps students solve real-world problems and find solutions to complex issues (Jang, 2016). Additionally, the use of differentiated learning processes can develop students' critical thinking skills because it provides learning that matches their characteristics and needs (Avandra & Desyandri, 2022; Solikhin et al., 2023). This enables students to explore the material and build understanding based on their abilities, while also gaining confidence to participate in problem-solving processes.

The results of the study indicate that PBL-STEM-Differentiated has a positive effect on students' critical thinking skills. However, the achievement percentage data for the critical thinking skills indicators (Fig-3) reveals that both the experimental and control classes have the lowest percentage in the interpretation indicator. This is evident from the learning process, where only a few students were active and accurate in identifying information and problems at the early stages. This could be due to students' difficulty in converting narrative problems into mathematical or simpler forms, the challenge of integrating abstract chemistry concepts, and a lack of reasoning ability, which made it difficult for them when presented with narrative and analytical problem variations.

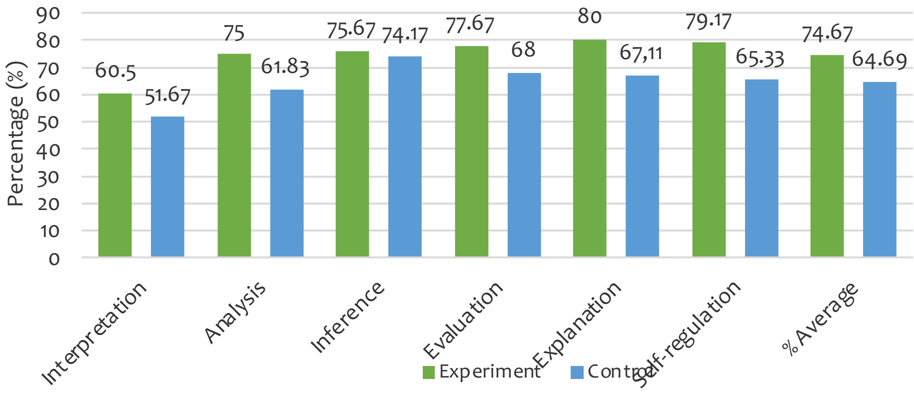

Fig-3. Critical thinking skills achievement percentage

Meanwhile, the highest percentage in the experimental class was observed in the fifth indicator, explanation, while in the control class, it was in the inference indicator. This occurred because students in the experimental class were more actively engaged, providing opportunities to practice giving detailed, concrete, and relevant explanations according to their abilities. Therefore, the experimental group was able to provide explanations that aligned with the instructions in the posttest. In contrast, in the control class, only a few students were active during learning, and their skills were less developed, as seen from the limited posttest responses focused only on the conclusion.

This was reinforced by interviews with several students in the experimental class and the learning observation sheets, which showed that students in the advanced group were more enthusiastic and had a better understanding compared to those in the intervention or intermediate groups. This enthusiasm indicated active participation, which is part of learning motivation. The higher the motivation, the more likely students are to remain active in class, thereby supporting a higher level of critical thinking skills.

Conclusion

Based on the results of the study and data analysis, it can be concluded that there is a positive influence of the Differentiated STEM approach in problem-based learning model on students' critical thinking skills in the topic of basic chemistry laws. The implementation of the differentiated STEM approach in the experimental class yielded a significant effect in enhancing students' critical thinking skills compared to the standard problem-based learning model. By integrating the differentiated STEM approach in problem-based learning model, students are encouraged to actively engage in learning according to their respective skill levels, enabling each student to show consistency and significant improvement in their critical thinking skills. This is evident from the posttest average scores of the experimental class being higher than the control class (73.00 > 64.37) and the Kruskal-Wallis's hypothesis test showing a significance value of 0.004 (<0.05), which means there is an effect of the differentiated STEM approach in problem-based learning model on students' critical thinking skills.

Conflict of Interests

The author declares that there is no conflict of interest in this research and manuscript.

Acknowledgment

The author would like to thank the Institute for Research and Community Service, Sebelas Maret University, which has given a letter of assignment for implementing the Independent Scheme Research Number: 862/UN27.22/PT.01.03/2024.

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