



## STEM-Integrated Problem-Based Learning as a Cognitively Aligned Framework for Enhancing Critical Thinking in Thermochemistry

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### Abstract

Developing students' critical thinking skills remains a major challenge in chemistry education, particularly in thermochemistry, which requires conceptual, symbolic, and quantitative reasoning. While STEM-integrated problem-based learning (PBL-STEM) has gained increasing attention, limited studies have examined how this instructional approach aligns with the cognitive structure of critical thinking. This study investigated the effect of the PBL-STEM model on students' critical thinking skills in thermochemistry. A quasi-experimental design involving 64 tenth-grade students was employed. Participants were selected using purposive sampling and assigned to an experimental group and a control group. Critical thinking skills were measured using a 20-item essay test based on Facione's framework. The instrument demonstrated high reliability (Cronbach's  $\alpha = 0.915$ ) and strong content validity (CVI = 0.93). Data were analyzed using an independent-samples t-test. Results showed a significant difference between groups ( $t = 4.997$ ,  $p < 0.05$ ), with the experimental group achieving higher mean scores ( $M = 80.80$ ) than the control group ( $M = 65.38$ ). The effect size (Cohen's  $d = 1.25$ ) indicates a large instructional impact. These findings suggest that STEM-integrated PBL provides a cognitively aligned framework for fostering critical thinking in chemistry learning.

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## 1. INTRODUCTION

Thermochemistry is a branch of chemistry that studies the relationship between energy and the changes that occur during physical processes and chemical reactions. This concept is grounded in the Law of Conservation of Energy and involves several fundamental principles, including internal energy, enthalpy, entropy, and Gibbs free energy, which are used to explain the magnitude of energy involved in a system (Finkenstaedt-Quinn et al., 2020). In the Grade XI science curriculum at the senior secondary level, thermochemistry is presented through topics such as enthalpy changes and the formulation of thermochemical equations, emphasizing both conceptual understanding and computational skills (Gusmilasari et al., 2020). However, the complexity of this subject often leads to

learning difficulties, as it involves abstract concepts that cannot be directly observed but must instead be understood through calculations and indirect effects. This situation highlights the need for effective instructional strategies to address these challenges.

The urgency of studying thermochemistry extends beyond mere content mastery; it is also essential in everyday contexts, such as understanding combustion processes, metabolic reactions, and energy changes in closed and open systems (Rahmawati et al., 2021). Therefore, thermochemistry instruction should be designed to foster strong conceptual understanding and applicable problem-solving skills. Moreover, chemistry learning should ideally serve as a medium for developing higher-order thinking skills through real-world relevant

activities, thereby promoting students' learning motivation and scientific attitudes.

Thermochemistry encompasses various subtopics, including the measurement of heat of reaction under constant volume and constant pressure conditions, the calculation of enthalpy changes ( $\Delta H$ ) based on standard enthalpy of formation data ( $\Delta H^\circ_f$ ), the application of Hess's Law, and the use of bond energies to predict chemical reactions (Hidayat et al., 2024). To master this material, students must first understand the fundamental concepts before proceeding to more complex mathematical computations. Failure to comprehend these foundational concepts often results in difficulties in solving chemical calculations, ultimately leading to low learning achievement in this topic.

Several studies indicate that students encounter significant obstacles in understanding thermochemistry concepts. These difficulties include distinguishing between heat and temperature, identifying exothermic and endothermic reactions, and understanding the roles of systems and surroundings in calorimetry experiments (Hidayat et al., 2024; Rosyidah et al., 2024). Research has shown that a considerable proportion of students still experience misconceptions related to enthalpy changes, thermochemical reactions, and energy transfer processes, which often arise from limited conceptual understanding and insufficient interactive learning experiences (Pahriah et al., 2025). When these misconceptions persist, they can hinder students' ability to analyze chemical phenomena and interpret energy–reaction relationships, which are essential components of scientific reasoning and critical thinking in chemistry learning.

One approach considered promising for addressing conceptual difficulties in thermochemistry is the implementation of simple laboratory activities, such as the use of self-constructed calorimeters. This approach enables students to build understanding through direct experience and real interaction with the phenomena under study (Komalia et al., 2024). However, laboratory implementation is often constrained by limited equipment, time allocation, and teachers' readiness to systematically connect practical experiences with theoretical explanations. Therefore, the effectiveness of this approach largely depends on well-designed activities integrated with clear pedagogical strategies.

Alternatively, technology-based media such as educational games have been introduced in chemistry learning. One example is *The Legend of Thermo*, an interactive medium designed to visualize complex thermochemical concepts and enhance students' learning motivation through a game-based approach (Uyun & Lutfi, 2022). Although such media provide engaging learning experiences, their effectiveness depends heavily on the availability of digital infrastructure, teachers' facilitation skills, and appropriate activity management to ensure that learning does not merely become entertainment.

Another instructional approach proven effective in developing students' critical thinking skills is Argument-Driven Inquiry (ADI). This model is grounded in scientific inquiry principles that require students to identify problems, collect data, construct evidence-based arguments, and present investigative reports that are subsequently revised through reflective interaction (Purwandari et al., 2023). Although ADI has been shown to be more effective than conventional approaches in fostering critical thinking skills, within the context of complex chemistry topics, it has not fully addressed the need for contextualized and integrated learning.

In seeking instructional models that enhance the effectiveness of conceptual understanding in chemistry, attention must also be directed toward critical thinking skills as a key indicator of higher-order thinking. Critical thinking involves logical, reflective, and rational processes in decision-making based on objective criteria, including problem formulation, data analysis, information interpretation, and argument evaluation (Sudirman & Yusnaeni, 2020). Its relevance in chemistry education is substantial, as critical thinking not only supports conceptual understanding but also develops students' ability to systematically solve real-world problems. Therefore, instructional models should be explicitly designed to facilitate the development of these skills.

In response to this need, the present study proposes the implementation of a PBL–STEM instructional model that integrates Problem-Based Learning with STEM (Science, Technology, Engineering, and Mathematics) principles. Through the presentation of real-world problems connected to scientific, technological, engineering, artistic, and mathematical contexts, students are encouraged to conduct investigations, design solutions, and develop projects as

forms of problem-solving, thereby fostering critical and creative thinking skills (Chusna et al., 2024).

The PBL–STEM model is structured into five instructional phases: problem orientation, student organization, independent investigation, development and presentation of outcomes, and analysis and reflection. Each phase encourages students to understand authentic problems, engage in exploration integrating science, technology, engineering, arts, and mathematics, and produce contextualized and creative solutions. This model promotes collaboration, enhances critical thinking skills, and increases students' learning motivation (Hariaji et al., 2024). The primary strength of PBL–STEM lies in its capacity to integrate scientific concepts with everyday life, thereby making learning more meaningful and relevant to 21st-century challenges.

Previous studies have demonstrated that the implementation of the PBL–STEM model significantly improves students' critical, collaborative, and creative thinking skills. Learning activities centered on authentic problem-solving with the integration of science, technology, engineering, arts, and mathematics encourage students to generate innovative solutions and construct logical, evidence-based arguments (Hariaji et al., 2024).

Although previous studies have reported the effectiveness of PBL–STEM in improving students' critical thinking skills, most investigations have focused on general science topics or mathematics and physics contexts. Limited research has specifically examined the implementation of STEM-integrated PBL in thermochemistry, a topic characterized by abstract concepts and complex energy transformations. Furthermore, prior studies often emphasize overall learning outcomes without providing a detailed analysis of improvements across specific critical thinking indicators. Consequently, there remains a need for empirical evidence that systematically investigates how PBL–STEM influences distinct dimensions of critical thinking—namely interpretation, analysis, evaluation, inference, and explanation—within the context of thermochemistry instruction.

Within the broader landscape of global STEM education research, numerous studies have demonstrated that integrating STEM principles into inquiry-based or problem-based pedagogies can enhance higher-order thinking skills (e.g., Pérez Torres et

al., 2024; Rahmadani et al., 2025). However, much of the international literature tends to report overall gains in critical thinking or general academic achievement without systematically examining how specific critical thinking dimensions develop within conceptually demanding chemistry topics. In particular, limited attention has been given to how STEM-integrated PBL operationalizes distinct cognitive processes—such as interpretation, evaluation, and inference—within abstract domains like thermochemistry, where symbolic representation, quantitative reasoning, and energy conceptualization intersect. Thus, beyond contextual application, a conceptual gap remains regarding how interdisciplinary STEM inquiry structurally aligns with established critical thinking frameworks in chemistry learning. Addressing this gap is essential for advancing both theoretical refinement and instructional design in STEM-based chemistry education.

Therefore, the novelty of this study lies in its focused application of the PBL–STEM model to thermochemistry learning at the senior secondary level and its comprehensive measurement of critical thinking development across multiple indicators. This study contributes to the growing body of STEM education research by providing empirical evidence of the model's effectiveness in addressing conceptual abstraction while simultaneously fostering higher-order thinking skills in chemistry education.

Based on these considerations, this study aims to examine the effect of integrating STEM into the Problem-Based Learning model on Grade XI students' critical thinking skills in thermochemistry, thereby addressing the identified research gap and contributing empirical evidence to support innovative instructional practices in chemistry education.

## 2. METHOD

### 2.1. Research Design and Participants

This study employed a quasi-experimental design involving two classes/groups (with 64 students, comprising 35 students in the experimental group and 29 students in the control group) of second-year students at MAN 1 Kota Gorontalo taking chemistry class. A purposive sampling technique was employed to select two intact classes from Grade XI science students at MAN 1 Kota Gorontalo. The selection was based on several criteria: (1) both classes had comparable academic

achievement levels in previous chemistry assessments, (2) the classes were taught by the same chemistry teacher to minimize instructional variability, and (3) the school administration permitted the implementation of different instructional treatments in these classes. Based on these considerations, one class was assigned as the experimental group, which received instruction through the PBL–STEM model, while the other class served as the control group and was taught using conventional instructional methods. An initial comparison of pretest scores was conducted to ensure that no statistically significant difference existed between the two groups prior to the intervention. Furthermore, the homogeneity test using Levene's Test ( $p > 0.05$ ) indicated that the variances of the two groups were homogeneous, confirming the comparability of their prior academic ability.

## 2.2. Research Instrumen

The instrument employed in this study was a critical thinking skills test consisting of 20 essay items designed to measure five indicators of critical thinking based on (Facione, 2015) framework: interpretation, analysis, evaluation, inference, and explanation. Each item was constructed to align with both the critical thinking indicators and the key concepts of Thermochemistry.

Content validity was established through expert judgment involving three experts in chemistry education and educational assessment. The experts evaluated each item in terms of relevance, clarity of construction, and alignment with the critical thinking indicators and thermochemistry content using a structured rating scale. The content validity index was calculated using (Aiken, 1985) formula, and the analysis yielded a validity coefficient of 0.93. This value falls within the "very high" validity category ( $V \geq 0.80$ ), indicating that the items demonstrate strong representativeness and alignment with the intended construct. Therefore, the instrument was considered appropriate and valid for measuring students' critical thinking skills in thermochemistry.

The scoring of essay responses was conducted using an analytic rubric developed for each critical thinking indicator. Each item was scored on a scale of 0–4, where 0 indicated an incorrect or irrelevant response, and 4 represented a complete, scientifically accurate, and well-reasoned answer. The total possible score was then converted into percentage form for analysis.

The instrument demonstrated excellent internal consistency reliability, with a Cronbach's Alpha coefficient of 0.915, categorized as very high. The test was administered within a 120-minute session, which was deemed sufficient based on preliminary trial implementation to ensure feasibility and allow students.

## 2.3. Data Analysis

The data analysis was conducted in several systematic stages. First, descriptive statistics were calculated in percentage form to describe students' critical thinking skills before and after the intervention.

Second, prerequisite assumption tests were performed. The normality of the data distribution was examined using the Kolmogorov–Smirnov test, while homogeneity of variance between groups was assessed using Levene's Test.

Based on the results of the assumption testing, appropriate inferential statistical procedures were selected. When the assumptions of normality and homogeneity were satisfied, an independent samples t-test was conducted to compare posttest scores between the experimental and control groups. All statistical analyses were performed using SPSS Statistics 29 with a significance level of 0.05.

In addition to statistical significance testing, effect size measures were calculated to determine the magnitude of the intervention effect. Cohen's *d* was used to estimate the effect size for the independent samples comparison, providing an interpretation of the practical significance of the PBL–STEM intervention (Cohen, 1988).

## 3. RESULT AND DISCUSSION

### 3.1. Result

#### Students' Critical Thinking Skills in Thermochemistry

The measurement of students' critical thinking skills was conducted through a pretest and a posttest. The pretest was administered to identify students' prior knowledge before the implementation of the STEM-based PBL instructional model. Meanwhile, the posttest was used to determine the improvement in students' critical thinking skills after participating in the learning process using the model.

Based on the results of data analysis, the mean pretest and posttest scores for experimental groups,

reviewed according to the indicators of critical thinking skills, are presented in Table 1.

Based on the data presented in Table 1, it can be inferred that the critical thinking skills of students taught using the STEM-based Problem-Based Learning (PBL) model in the experimental group were higher than those of students in the control group who were taught using the lecture method. However, this assumption must be statistically verified through inferential analysis using an independent samples t-test.

Table 1. Percentage (%) of Students' Critical Thinking Skill Indicators in the Pretest and Posttest Results of two Classes

Students' Critical Thinking Skill Indicators	Pre-test (%)	Post-test (%)	Pre-test (%)	Post-test (%)
Interpretation	38,73	72,32	44,48	88,70
Analysis	29,47	65,81	37,14	81,06
Evaluation	25,30	49,40	26,07	72,80
Inference	10,30	45,50	13,10	58,30
Explanation	50,70	73,10	46,47	82,27

### The Effect of the Integrating STEM Into Problem-Based Learning (PBL) Model on Students' Critical Thinking Skills

The Effect of the Integrating STEM Into Problem-Based Learning (PBL) Model on Students' Critical Thinking Skills testing in this study was conducted using independent-samples comparison tests. The independent-samples comparison test was conducted to examine differences in the mean critical thinking skills between students in the experimental and control groups. The data analyzed in this stage consisted of the posttest scores from both groups.

Prior to hypothesis testing, prerequisite analyses were performed. Normality was assessed using the Kolmogorov-Smirnov test, which yielded a significance value of 0.200, indicating that the data were normally distributed ( $p > 0.05$ ). Homogeneity of variance was examined using Levene's Test, resulting in a significance value of 0.071, suggesting that the variances of the two groups were homogeneous ( $p > 0.05$ ).

Since both assumptions of normality and homogeneity were satisfied, the analysis proceeded using a parametric independent-samples t-test to determine whether there was a statistically significant

difference between the two groups. The results of the independent-samples t-test revealed a statistically significant difference in posttest scores between the experimental and control groups ( $t = 4.997$ ;  $p < 0.05$ ). Students in the experimental group ( $M = 80.80$ ,  $SD = 9.695$ ) outperformed those in the control group ( $M = 65.38$ ,  $SD = 14.843$ ).

To determine the magnitude of the instructional effect, Cohen's  $d$  was calculated and yielded a value of 1.25, indicating a very large effect size. This finding suggests that the PBL-STEM model had not only statistical significance but also substantial practical impact on students' critical thinking skills. Therefore, it can be concluded that the PBL-STEM model significantly and meaningfully enhances students' critical thinking skills in Thermochemistry.

### 3.2. Discussion

The findings of this study demonstrate that the implementation of the PBL-STEM model resulted in a consistent and substantial improvement across all dimensions of critical thinking. Rather than functioning as isolated competencies, interpretation, analysis, evaluation, inference, and explanation developed in an interconnected manner. This integrated improvement suggests that the instructional structure of PBL-STEM systematically supports the development of higher-order thinking skills. These findings are consistent with previous studies reporting the effectiveness of PBL-STEM in enhancing critical thinking abilities (Awaludin et al., 2025; Hadi, 2021; Khoirunnissa et al., 2024).

From a theoretical perspective, critical thinking comprises coordinated cognitive processes involving interpretation, analysis, evaluation, inference, and explanation, as conceptualized by (Facione, 2015). The PBL-STEM instructional syntax appears to operationalize these dimensions coherently. During the problem-orientation phase, students engage in interpreting contextual thermochemical phenomena, identifying relevant variables, and clarifying problem situations. This stage strengthens interpretative competence, which forms the foundation for deeper analytical reasoning. Similar findings were reported by (Azzahra & Putri, 2025; Nurkhalizah & Santosa, 2025), who emphasized that contextual STEM-based learning enhances students' ability to interpret information meaningfully.

As learning progresses into the organization and investigation phases, students deconstruct problems, connect thermochemical principles such as enthalpy changes and energy conservation, and evaluate alternative solution strategies. This structured engagement fosters analytical and evaluative reasoning. (Ratnasari & Sulistyningrum, 2023) and (Hasani et al., 2024) similarly found that STEM-integrated PBL significantly improves students' analytical reasoning through systematic problem-solving activities. Furthermore, empirical reviews by (Putri et al., 2023) indicate that interdisciplinary STEM learning strengthens students' capacity to relate conceptual understanding to real-world applications.

The evaluative and inferential dimensions are particularly strengthened through collaborative investigation and evidence-based discussion. Students are required to assess the credibility of data, compare possible solutions, and justify conclusions logically. This process cultivates reflective judgment, a core characteristic of advanced critical thinking. Studies by (Wiwita et al., 2025) corroborate that STEM-based PBL enhances students' ability to evaluate information and construct reasoned arguments. Similarly, Sri Hartati & Rahayu, (2023) demonstrated that integrating STEM within PBL supports inferential reasoning by engaging learners in data analysis and collaborative synthesis.

The improvement observed in the explanation indicator further highlights the pedagogical strength of PBL–STEM. The requirement for students to present solutions and defend their reasoning promotes metacognitive awareness and structured argumentation. This aligns with findings from Asti & Andriyani, (2022) and (Nurkhalizah & Santosa, 2025), who reported that STEM-oriented PBL enhances students' explanatory competence through systematic justification and reflective communication.

The effectiveness of STEM-integrated PBL in this study is consistent with prior empirical findings in chemistry education. For instance, (Gusman et al., 2023) reported that STEM-integrated problem-based learning significantly improved students' critical thinking skills in electrolyte and non-electrolyte solution topics. Similarly, (Nurdiana et al., 2024) found that STEM-integrated project-based learning enhanced critical thinking through structured lesson study implementation. These findings reinforce the argument that combining inquiry-based

pedagogy with interdisciplinary STEM principles creates a cognitively demanding learning environment that fosters analytical and evaluative reasoning.

One major pedagogical mechanism underlying this improvement is contextualization. Thermochemistry is often perceived as abstract due to its symbolic representations and mathematical calculations. By embedding thermochemical concepts within authentic engineering or technological problems, students are encouraged to engage in contextualized reasoning rather than procedural computation. This aligns with Dibyantini et al., (2023), who demonstrated that STEM-based chemistry modules improve science literacy and learning motivation by situating abstract concepts within meaningful real-world contexts. Contextualization supports conceptual restructuring and facilitates knowledge transfer, which are essential components of critical thinking development.

Another key mechanism is active cognitive engagement through collaborative inquiry. In STEM-integrated PBL environments, students formulate hypotheses, analyze experimental data, evaluate solution alternatives, and justify conclusions. Such epistemic practices mirror authentic scientific reasoning processes. (Sari et al., 2021) showed that project-based learning integrated with chemistry instruction enhances both critical thinking and scientific literacy, particularly when students are required to communicate and defend their reasoning. Similarly, Tairas et al., (2024) emphasized that integrating STEM with PBL promotes deeper conceptual understanding and critical engagement through interdisciplinary collaboration.

The interdisciplinary dimension of STEM also plays a crucial role. Students must connect scientific principles with mathematical modeling, technological applications, and engineering design constraints. This multidimensional reasoning encourages learners to examine problems from multiple perspectives, which is a defining characteristic of advanced critical thinking. Linda & Arianingrum, (2025), in their systematic literature review, concluded that STEM implementation consistently strengthens students' analytical, inferential, and evaluative capacities by requiring cross-disciplinary synthesis and evidence-based justification.

Furthermore, the large effect size (Cohen's  $d = 1.25$ ) observed in this study indicates that the improvement is not only statistically significant but also

educationally meaningful. The magnitude of change suggests that the instructional alignment between PBL phases and STEM integration effectively facilitates reflective judgment and metacognitive awareness. During investigation and solution development, students must assess the credibility of data and justify conclusions based on thermodynamic principles. During presentation phases, they are required to articulate reasoning coherently and defend arguments logically. These structured processes cultivate explanation and inference skills as integral components of critical thinking.

Unlike conventional instruction, which frequently emphasizes algorithmic problem solving in thermochemistry, the STEM-integrated PBL model restructures learning around inquiry, interdisciplinary reasoning, and evidence-based argumentation. This pedagogical shift transforms thermochemistry from a computationally dominated topic into a conceptual-contextual domain that fosters integrated reasoning and deeper cognitive engagement.

Collectively, these findings provide empirical support for positioning STEM-integrated PBL as a cognitively aligned pedagogical framework for developing higher-order thinking in chemistry education. By intentionally integrating authentic problem contexts, collaborative inquiry, and interdisciplinary reasoning, the model systematically cultivates interpretation, analysis, evaluation, inference, and explanation skills. Therefore, this study contributes to the growing body of evidence indicating that critical thinking development is optimized when instructional design deliberately aligns problem-based inquiry with integrated STEM principles.

#### 4. CONCLUSION

This study demonstrates that STEM-integrated Problem-Based Learning (PBL-STEM) significantly improves students' critical thinking skills in thermochemistry compared to conventional instruction. The substantial effect size (Cohen's  $d = 1.25$ ) indicates that the impact is not only statistically significant but also educationally meaningful. The findings contribute theoretically by reinforcing the alignment between interdisciplinary STEM inquiry and established critical thinking frameworks. Practically, the study provides empirical support for adopting PBL-STEM as an instructional approach capable of fostering higher-order thinking in complex chemistry topics. However, this

research was limited to a single school context and focused on short-term instructional implementation. Future studies should examine long-term effects, broader samples, and potential mediating variables such as scientific reasoning or metacognitive awareness.

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