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STEM-PBL Instructional Materials to Support Quality Education through Chemical Literacy in Thermochemistry

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Abstract: The purpose of this study was to evaluate the effectiveness of STEM-Problem Based Learning (STEM-PBL) instructional materials in improving students' chemical literacy on thermochemistry topics. This study employed a quasi-experimental method using a pretest-posttest control group design. The participants were 56 Chemistry Education students divided into an experimental class and a control class, each consisting of 28 students. Data were collected using a validated and reliable essay test (Cronbach's $\alpha = 0.85$). The results showed that the experimental class improved from 36.11 to 88.50, while the control class improved from 31.50 to 78.43. An independent samples t-test revealed a significant difference between the two groups ($p < 0.05$). In addition, the effect size analysis yielded a Cohen's d value of 1.16, indicating a large effect. These findings suggest that STEM-PBL instructional materials effectively improve students' chemical literacy, particularly in conceptual understanding, critical thinking, and problem-solving related to thermochemistry. In conclusion, STEM-PBL instructional materials are effective and feasible for enhancing chemical literacy and supporting quality, contextual, and 21st-century-oriented chemistry learning at the university level.

Keywords: Chemical literacy; Instructional materials; Quality education; STEM-PBL; Thermochemistry

Introduction

Advances in science and technology in the 21st century require individuals not only to master concepts but also to possess critical thinking skills, creativity, collaboration, and communication skills when addressing real-world problems (Mutlu & Şeşen, 2016). In this context, chemical literacy has become a critical competency encompassing conceptual understanding, the interpretation of scientific phenomena, the evaluation of scientific information, and responsible decision-making regarding health, environmental, and technological issues (Peña-Martínez et al., 2025). Chemical literacy is no longer viewed merely as conceptual mastery but as an applied ability integrated with higher-order thinking skills and social awareness (Tholibon et al., 2022). However, the fact that chemistry learning remains predominantly theoretical has prevented chemistry literacy from developing optimally, particularly in linking concepts to real-world contexts and authentic problem-solving, thereby resulting in low levels of chemical literacy and science-based decision-making skills (Setyorini et al., 2024).

The importance of chemical literacy can be explained through constructivist learning theory, which emphasizes that knowledge is actively constructed by learners through interaction with experiences and meaningful learning activities. According to constructivist principles, students develop deeper understanding when they are engaged in authentic problems and are encouraged to connect new information with prior knowledge. This perspective is consistent with the STEM-PBL approach, which places students at the center of learning through inquiry, collaboration, and contextual problem-solving. Furthermore, situated learning theory suggests that learning becomes more meaningful when knowledge is acquired and applied within real-life contexts.

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Therefore, integrating thermochemistry concepts with authentic problems through STEM-PBL is expected to facilitate the development of chemical literacy and higher-order thinking skills. In addition, Mayer's Cognitive Theory of Multimedia Learning explains that well-designed instructional materials can improve conceptual understanding by presenting information through multiple representations, enabling students to process, organize, and integrate knowledge more effectively.

By integrating science, technology, engineering, and mathematics into practical problem-solving, the STEM-PBL approach effectively develops chemistry literacy and 21st-century abilities (Dewi et al., 2025). According to Agussuryani et al. (2022), this method helps students apply chemical principles contextually, collaborate with others, and develop solutions based on scientific evidence. Research also indicates that STEM-PBL successfully improves students' chemical literacy and conceptual understanding (Karmila & Putra, 2022). Furthermore, STEM-PBL enhances students' ability to explain scientific phenomena, evaluate scientific information, and understand the impact of chemistry on society and the environment (Anugrahsari et al., 2025). It also fosters communication, teamwork, and technology utilization skills (Salsabila & Sari, 2024). The integration of chemical literacy into STEM-PBL is aligned with sustainable development issues and global challenges such as green chemistry and waste management (Khalda et al., 2025).

Problem-Based Learning (PBL) utilizes real-world problems to promote student-centered learning and enhance student engagement (Mudrikah et al., 2020). The integration of PBL with the STEM approach has proven effective in developing collaboration, communication, investigation skills, and contextual understanding through group discussions and problem-solving activities (Rosana et al., 2022). Unlike Project-Based Learning (PjBL), which emphasizes the development of products or final projects, PBL focuses primarily on problem analysis and solution processes (Sofyan et al., 2025). Therefore, this study specifically adopts the STEM-PBL approach because it is considered more suitable for strengthening students' chemical literacy through contextual problem-solving activities (Sun et al., 2021). In addition to the learning approach, learning success is also supported by the availability of systematic teaching materials, such as modules, which facilitate understanding of the material and encourage active student participation (Ma et al., 2020; Shamsudin et al., 2026).

Chemistry education today still tends to be teacher-centered, with the instructor serving as the primary source of information; as a result, students lack independence and face learning difficulties due to limited instructional materials In introductory chemistry courses, particularly in thermochemistry, students still find the material difficult to understand research specifically examining the effectiveness of STEM-PBL instructional materials, and the available instructional materials have not yet optimally integrated the STEM-PBL approach (Rosdiana et al., 2026). In fact, thermochemistry learning linked to everyday problems has the potential to improve students' chemical literacy because students are encouraged to relate chemical concepts to real-life situations and scientific decision-making. Therefore, the development of STEM-PBL-based instructional materials is needed to support students in understanding thermochemistry concepts contextually (Rokhimawan et al., 2022).

Thermochemistry, a branch of chemistry that examines heat changes in chemical reactions, is considered difficult by both high school and university students (Pertiwi, 2019). Understanding concepts such as exothermic and endothermic reactions, enthalpy changes, and combustion processes, as well as their practical applications, remains challenging (Rahmawati et al., 2021). Furthermore, the abundance of formulas and calculations in thermochemistry requires an integrative approach that combines science, mathematics, engineering, and technology to facilitate conceptual understanding (Wahyuningsih et al., 2025). In the STEM approach, the Engineering aspect can be implemented through activities such as designing a simple calorimeter or developing a thermal insulation system, enabling students to connect mathematical calculations with real-world applications (Formentin, 2023). Therefore, thermochemistry is highly relevant to be integrated with STEM-PBL because it has strong connections to various phenomena encountered in everyday life (Allamin et al., 2018).

Several studies have demonstrated the effectiveness of STEM-based learning in improving science literacy and learning outcomes compared to conventional learning approaches (Wahyu et al., 2020). STEM-based learning also supports the integration of cognitive and psychomotor learning outcomes through contextual learning stages (Muzana et al., 2021). Research further indicates that students who learn using STEM-integrated PBL instructional materials achieve better learning outcomes than those who use conventional approaches (Khairani et al., 2025). In another study, STEM-based PBL instructional materials for green chemistry were validated in terms of content, presentation, language, STEM integration, and graphics, and received positive responses from students (Putri et al., 2026).

Research on chemical literacy continues to develop because this competency is essential in 21st-century science education (Nanda & Agustini, 2023). Chemical literacy encompasses the ability to understand, apply, evaluate, and communicate chemical concepts in real-world contexts (Putri et al., 2023). Although previous studies have mostly focused on secondary education, recent research has increasingly emphasized the importance of chemical literacy in higher education contexts, particularly in relation to contextual learning, authentic problem-solving, and sustainability issues (Alvina et al., 2025). However, research specifically examining the effectiveness of STEM-PBL instructional materials in improving students' chemical literacy on thermochemistry topics at the higher education level remains limited (Juniarti & Musaddat, 2025).

The STEM-PBL approach is increasingly used to strengthen chemical literacy through the integration of chemistry concepts, technology, engineering activities, and contextual problem-solving. Previous studies have shown that STEM-PBL effectively improves students' science literacy, conceptual understanding, and creativity, particularly in complex chemistry topics such as thermochemistry (Fairuza et al., 2023). In addition, Problem-Based Learning (PBL), as an essential component of STEM-PBL, has been widely applied in chemistry education and has demonstrated positive contributions to students' chemical literacy through real-world problem analysis and collaborative learning activities (Mulyati et al., 2024). Although most previous studies were conducted at the secondary education level, the implementation of STEM-PBL in higher education remains limited, especially in thermochemistry learning (Hidayah et al., 2025). Therefore, adapting the STEM-PBL approach in higher education is important to support students' chemical literacy and contextual understanding in accordance with 21st-century learning demands (Tairas et al., 2025).

Several previous studies, such as "Development of General Chemistry Teaching Materials Using the PjBL-STEM Model," developed project-based STEM instructional materials for higher education and reported moderate to high N-Gain values (≥0.55) in improving students' creative thinking skills (Arisa & Sitinjak, 2022). In addition, expert validation results indicated a feasibility level of 90.00%, showing that the instructional materials were appropriate for implementation in chemistry learning (Purba et al., 2024). However, these studies focused on the PjBL approach, which emphasizes product development, whereas the present study focuses on STEM-PBL, which emphasizes contextual problem-solving processes to strengthen chemical literacy.

The project entitled "Development of a STEM-PBL-Based Teaching Module Integrated with Scientific Literacy in Electrochemistry" produced instructional materials that successfully integrated scientific literacy into contextual electrochemistry learning. The results demonstrated that the developed module was suitable for use as an innovative teaching material capable of integrating problem-solving activities with the reinforcement of scientific literacy and 21st-century skills (Dibyantini et al., 2024). These findings indicate that STEM-PBL has strong potential to be implemented in other chemistry topics, including thermochemistry, which requires contextual understanding and real-world problem analysis (Arafani et al., 2025).

The integration of chemical literacy, STEM-PBL, and 21st-century skills represents a promising direction in chemistry education. However, its implementation in higher education, particularly in thermochemistry learning, remains limited. Previous studies also emphasized the need for specifically designed instructional materials, such as modules, e-modules, or thermochemistry-based projects, to support the development of students' chemical literacy holistically in accordance with 21st-century learning demands (Fitriyani et al., 2023). Therefore, this study offers novelty by developing and evaluating STEM-PBL instructional materials specifically designed to improve students' chemical literacy in thermochemistry learning at the higher education level (Noordin & Karunanithi, 2026. The findings of this study are expected to contribute to the development of innovative, contextual, and student-centered chemistry instructional materials that support 21st-century learning competencies holistically.

Method

This study employed a Research and Development (R&D) approach combined with a quasi-experimental design using a pretest-posttest control group design to evaluate the effectiveness of STEM-PBL instructional materials in improving students' chemical literacy on thermochemistry topics (Barcelona & Cruz, 2025). The development of the instructional materials adopted the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. The population of this study consisted of all 2022-intake Chemistry Education students enrolled in the General Chemistry course at Universitas Negeri Medan across five classes. The sample consisted of two intact classes with 28 students in each class selected using cluster random sampling. One class was assigned as the experimental class using STEM-PBL instructional materials, while the other served as the control class using conventional instructional materials. Because the subjects were not randomly assigned individually into groups, this study was categorized as a quasi-experimental design. Before implementation, the developed instructional materials were validated by experts in chemistry content, instructional media, and language to ensure their feasibility and appropriateness for learning. After the validation stage, a pilot study was conducted to evaluate the effectiveness of the instructional materials in classroom learning.

The research instrument consisted of 5.00 validated and reliable essay questions designed to measure students' chemical literacy. The instrument assessed several indicators of chemical literacy, including understanding chemical concepts, interpreting scientific phenomena in daily life contexts, analyzing thermochemistry-related problems, and applying scientific reasoning in decision-making processes. The effectiveness of the instructional materials was evaluated based on students' pretest and posttest learning outcomes. Data analysis was conducted using SPSS version 26.00. Prior to hypothesis testing, normality and homogeneity tests were performed. The normality test used the Shapiro-Wilk test with the criterion that the data were normally distributed if sig. > 0.05. The homogeneity test was conducted using Levene's Test on the pretest scores to ensure that both groups had equivalent initial abilities before receiving treatment. The data were considered homogeneous if sig. > 0.05.

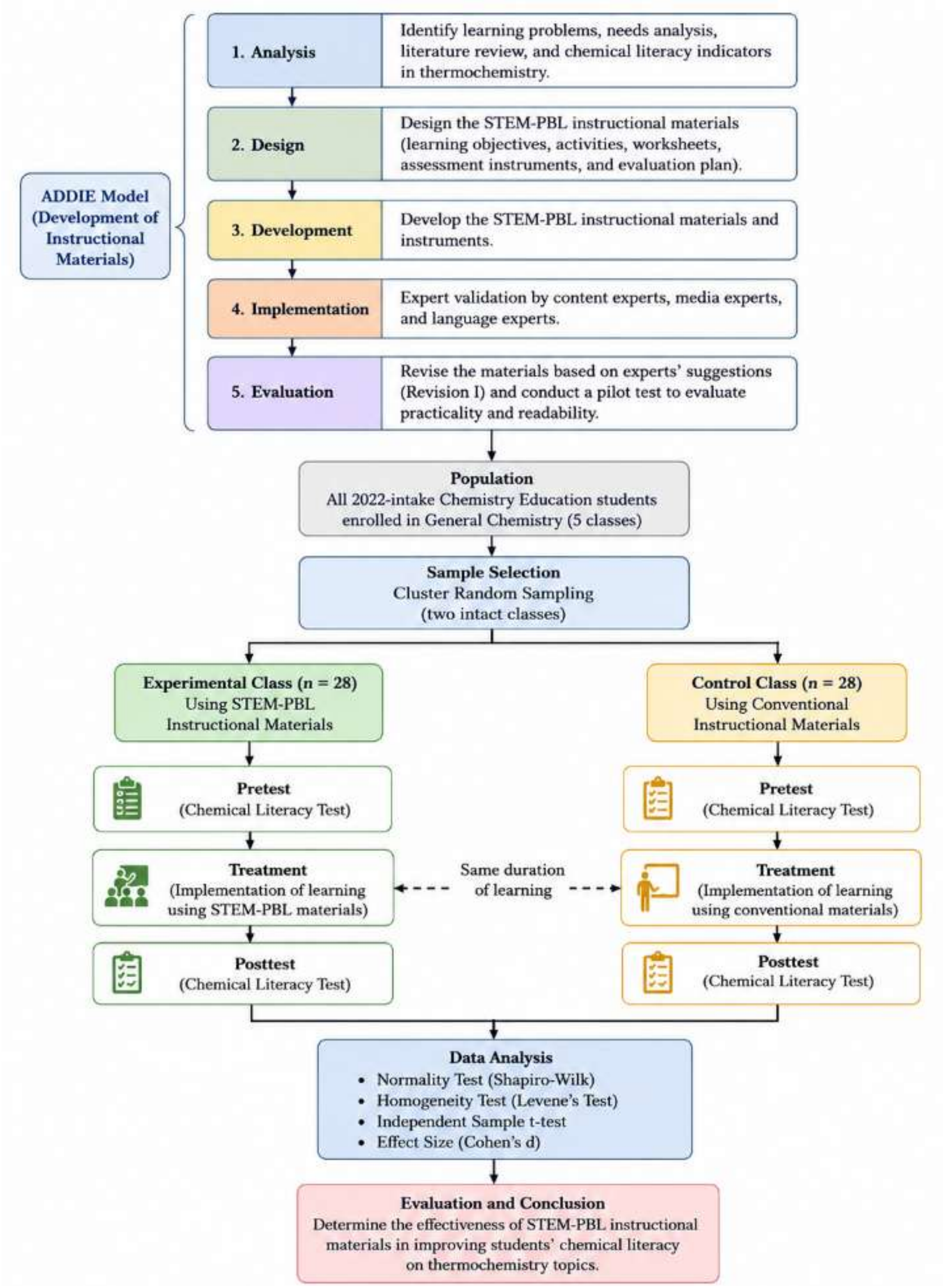

Figure 1. Research procedure

Furthermore, the hypothesis test was conducted using the Independent Sample t-test with the criterion that there was a significant difference between the experimental and control groups if sig. < 0.05. The magnitude of the treatment effect was also analyzed using Cohen's d effect size to determine the practical significance of the STEM-PBL intervention. Cohen's d values were interpreted using the following criteria: 0.20 (small effect), 0.50 (medium effect), and 0.80 (large effect). The method was presented in Figure 1.

The research procedure is presented in Figure 1. The study began with the analysis stage to identify learning problems and students' needs related to chemical literacy in thermochemistry. The instructional materials were then designed and developed using the ADDIE model. After undergoing expert validation and revision, the instructional materials were implemented in the experimental class, while the control class received conventional instruction. Both groups completed pretests and posttests to measure chemical literacy achievement. The collected data were analyzed using normality and homogeneity tests, followed by an independent samples t-test and Cohen's d effect size analysis to determine the effectiveness of the developed STEM-PBL instructional materials.

Result and Discussion

The results of this study indicate that STEM-PBL-based instructional materials effectively improved students' chemical literacy in thermochemistry learning. The implementation of STEM-PBL encouraged students to actively engage in contextual problem-solving activities, collaborative discussions, and scientific reasoning processes related to thermochemistry concepts. Through the integration of Science, Technology, Engineering, and Mathematics, students were able to connect theoretical concepts with real-world applications, thereby supporting deeper conceptual understanding and improving chemical literacy skills.

This study was conducted in two classes, namely the experimental class and the control class, in the General Chemistry course on thermochemistry material. The experimental class received instruction using STEM-PBL-based instructional materials, while the control class learned using conventional instructional materials. The results obtained from this study included students' pretest and posttest scores in both classes, as presented in Table 1.

According to Table 1, the average pretest score of the experimental class was 36.11 with a standard deviation of 7.80, while the control class obtained an average score of 31.50 with a standard deviation of 5.17. These findings indicate that both groups had relatively similar initial abilities before the learning treatment was implemented. After the instructional process, the average posttest score of the experimental class increased to 88.50 with a standard deviation of 9.72, whereas the control class achieved an average score of 78.43 with a standard deviation of 7.44.

Table 1. Pretest and Posttest Results of Experimental and Control Classes

Data	Statistic	Experimental Class	Control Class
Pretest	Mean	36.11	31.50
	Standard Deviation	7.80	5.17
Posttest	Mean	88.50	78.43
	Standard Deviation	9.72	7.44

The improvement in students' scores demonstrates that learning using STEM-PBL-based instructional materials contributed more effectively to the enhancement of students' chemical literacy compared to conventional learning approaches. The experimental class experienced an increase of 52.39 points, while the control class increased by 46.93 points. In addition, the higher posttest score achieved by the experimental class indicates that STEM-PBL instructional materials supported students in understanding thermochemistry concepts more contextually and meaningfully, that shown in figure 2.

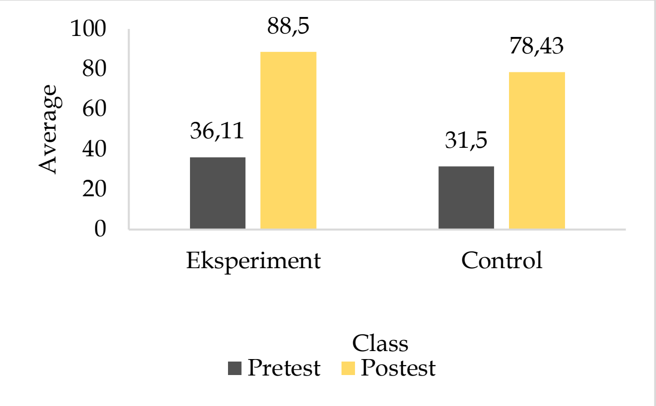

Figure 2. Average pretest and posttest scores of experimental and control classes

The effectiveness of STEM-PBL in this study can be explained through the integration of the STEM components during learning activities. The Science aspect helped students understand thermochemistry concepts scientifically, while the Mathematics aspect supported students in solving heat calculation problems systematically. Furthermore, the Engineering aspect encouraged students to design simple calorimeter models and analyze heat-transfer systems related to real-world situations. The Technology aspect supported learning through digital resources, interactive discussions, and contextual problem-solving activities. These integrated activities enabled students not only to memorize formulas but also to interpret scientific phenomena and apply scientific reasoning in everyday contexts, which are important components of chemical literacy.

Although this study did not specifically involve engineering activities in the form of designing or constructing a product, the learning process can still be categorized as STEM-PBL because the engineering aspect in STEM is not limited to physical product creation. In addition, Figure 2 illustrates the learning activities conducted using the STEM-PBL-based Thermochemistry book during the implementation of the learning process. In this study, students were engaged in thermochemistry experiments, digital simulations, heat analysis discussions, and contextual problem-solving presentations that reflect the engineering design process in learning activities. Through these activities, students identified problems related to heat and energy changes, analyzed experimental data, discussed possible solutions based on thermochemistry concepts, and communicated the results of their investigations. Therefore, the use of the STEM-Based Thermochemistry book still represents the integration of Technology and Engineering Process within the STEM-PBL approach. Furthermore, one component of the book, as illustrated in Figure 3, emphasizes how students analyze real-world problems, evaluate alternative solutions, and communicate scientific findings, which are essential characteristics of engineering thinking in STEM learning.

Figure 3. Students discussing thermochemistry problems using STEM-PBL instructional materials

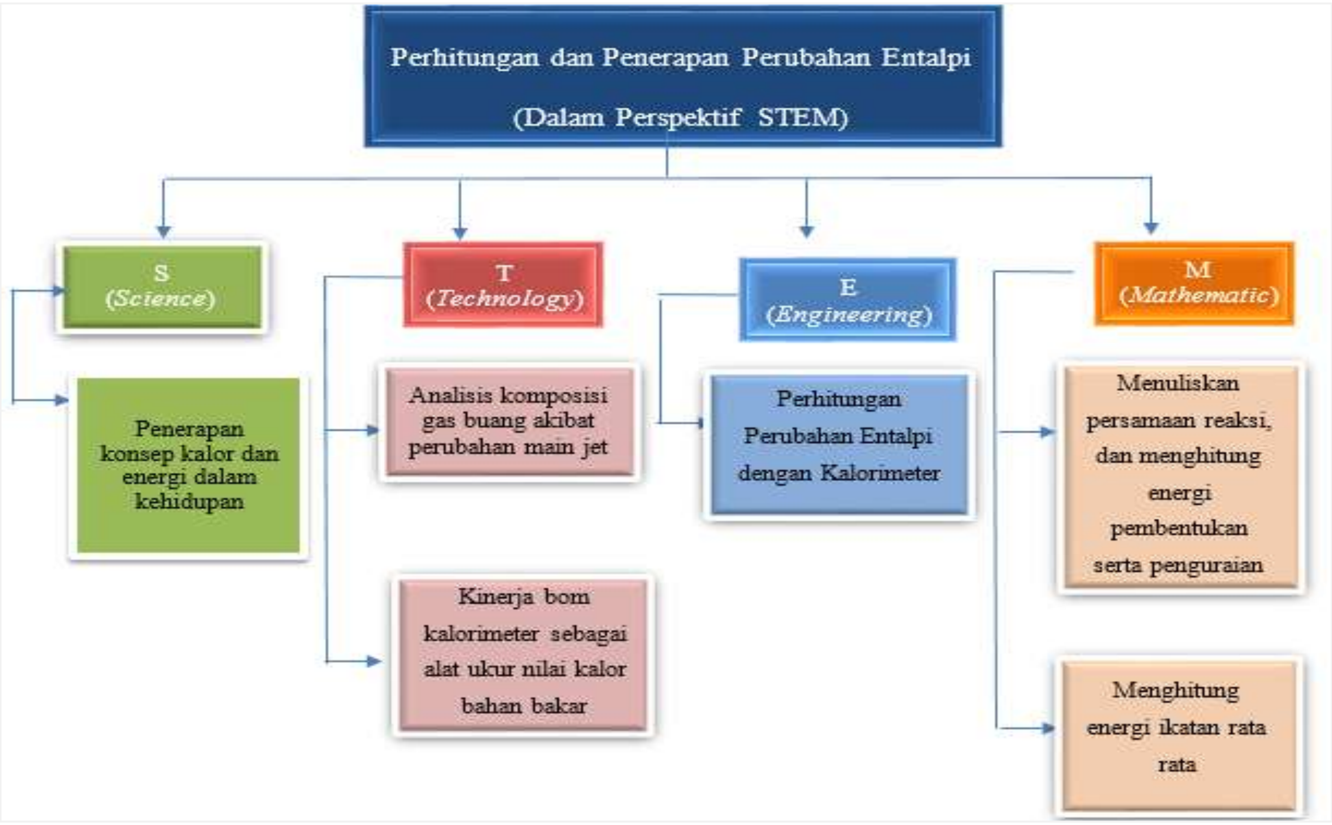

Figure 4. Students conducting engineering-based thermochemistry activities

Before conducting hypothesis testing, prerequisite tests consisting of normality and homogeneity tests were performed. The normality test results showed that the pretest and posttest data in both groups were normally distributed because all significance values were greater than 0.05. The results of the normality test are presented in Table 2.

Table 2. Results of the Normality Test for the Experimental and Control Classes

Class	Statistic	Sig.	α	Description
Experimental	Pretest	0.09	0.05	Normally Distributed
	Posttest	0.10	0.05	Normally Distributed
Control	Pretest	0.09	0.05	Normally Distributed
	Posttest	0.14	0.05	Normally Distributed

According to Table 2, all significance values were greater than 0.05, indicating that the data were normally distributed and met the assumptions required for parametric statistical analysis. Furthermore, the homogeneity test conducted on the pretest and posttest scores indicated that both groups had homogeneous variances since all significance values exceeded 0.05. The results of the homogeneity test are shown in Table 3.

Table 3. The Experimental and Control Groups' Homogeneity Test Results

Data	Sig.	α	Description
Pretest	0.33	0.05	Homogeneous
Posttest	0.34	0.05	Homogeneous

Based on Table 3, the significance values for both pretest and posttest scores were greater than 0.05, indicating that the experimental and control groups had homogeneous variances.

After the prerequisite assumptions were fulfilled, hypothesis testing was conducted using the Independent Sample t-test with the assistance of SPSS version 26.00. The statistical decision-making criterion stated that if the sig. value was less than 0.05, there was a significant difference between the experimental and control groups. The results of hypothesis testing are presented in Table 4.

Table 4. Hypothesis Testing

Data	Class	Average	Standard Deviation	Sig. (2-tailed)	α
Learning Outcomes (Postest)	Experimental	88.50	9.72	0.00	0.05
	Control	78.43	7.44	0.00	0.05

According to Table 4, the experimental class achieved a higher average score than the control class. The Independent Sample t-test produced a significance value (Sig. 2-tailed) of 0.00, which was lower than 0.05. Therefore, it can be concluded that there was a significant difference between the experimental and control groups. These findings indicate that STEM-PBL-based instructional materials significantly improved students' chemical literacy in thermochemistry learning.

The superiority of the experimental class compared to the control class indicates that STEM-PBL instructional materials successfully facilitated active and contextual learning experiences. Through problem-solving activities related to real-life thermochemistry phenomena, students became more engaged in analyzing scientific problems, discussing possible solutions, and applying chemical concepts to authentic situations. This learning process encouraged students to construct knowledge independently and improved their ability to evaluate scientific information critically.

The findings of this study are consistent with previous studies reporting that STEM-integrated Problem-Based Learning effectively improves students' chemical literacy and conceptual understanding. Fairuza et al. (2023) reported that STEM-PBL enhanced students' contextual problem-solving abilities and science literacy in chemistry learning. Similarly, Mulyati et al. (2024) found that the integration of PBL within the STEM framework significantly supported students' chemical literacy through collaborative learning and authentic scientific investigations. In addition, Khairani et al. (2025) demonstrated that STEM-based PBL instructional materials improved students' learning outcomes and conceptual understanding more effectively than conventional instruction.

The effect size analysis using Cohen's d produced a value of 1.16, which falls into the large effect category. This finding indicates that the difference between the experimental and control groups was not only statistically significant but also practically meaningful. The results of Cohen's d analysis are presented in Table 5.

Table 5. Cohen's d test

Key Values	Results
Cohen's d	1.16
95% CI	[0.60, 1.73]
Pooled SD	8.65
Proportion Overlap	56.06%
R Approximation	0.50
Magnitude Label	Large

According to Table 5, the Cohen's d value of 1.16 indicates a large effect size. The 95% confidence interval ranging from 0.60 to 1.73 further supports the strength of the intervention effect. In addition, the proportion overlap value of 56.06% indicates that the score distribution of the experimental group shifted substantially from that of the control group, strengthening the interpretation that the STEM-PBL intervention had a strong impact on students' chemical literacy.

The large effect size obtained in this study demonstrates that STEM-PBL-based instructional materials provide meaningful learning experiences that support students in understanding, analyzing, and applying thermochemistry concepts in contextual situations. Through collaborative investigations, engineering-based activities, and technology-assisted learning, students became more actively involved in the learning process and developed better scientific reasoning abilities. Therefore, both statistically and practically, STEM-PBL-based instructional materials can be considered effective in improving students' chemical literacy in thermochemistry learning.

Conclusion

The results of this study indicate that the implementation of STEM-PBL-based Thermochemistry teaching materials effectively improved students' chemical literacy in the experimental class compared to the control class. This finding is supported by the higher posttest average score achieved by the experimental class (88.50) than the control class (78.43), as well as the statistical test result showing a significant difference between the two classes (Sig. 0.00 < 0.05). Furthermore, the effect size analysis yielded a Cohen's d value of 1.16, which is categorized as a large effect, indicating that the intervention had substantial practical significance in enhancing students' chemical literacy and learning competencies. Therefore, the STEM-PBL-based Thermochemistry teaching material is considered feasible and highly effective as an alternative learning medium for Thermochemistry courses at the university level. Future research is recommended to apply this teaching material to broader chemistry topics and different educational levels in order to further examine its effectiveness in improving students' chemical literacy and problem-solving skills.

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Author Contributions
D.P.S. & M.A.N.: The writing and compiling drafts of research tools and instruments, including validation sheets and learning outcome test sheets, are currently up to the results stage, discussion of methodology, analysis, and conclusions; R.E.D. & A.J.P.: Currently in the validation process.

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Conflicts of Interest
The authors hereby declare no conflicts of interest.

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