JPPIPA 11(3) (2025)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

STEM-Integrated Problem-Based Learning in Green Chemistry to Enhance Chemical Literacy and Scientific Attitudes

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Received: December 15, 2024
Revised: February 13, 2025
Accepted: March 25, 2025
Published: March 31, 2025

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DOI: 10.29303/jppipa.v11i3.10666

Abstract: Students' low chemical literacy and scientific attitudes in understanding chemical concepts, particularly in green chemistry, pose significant challenges in chemistry education today. Traditional learning models are often less effective in fostering 21st-century skills, such as critical thinking and problem-solving, which are essential for a more relevant and applicable chemistry education. This study aims to evaluate the impact of a STEM integrated with Problem-Based Learning (PBL) model on students' chemical literacy and scientific attitudes in green chemistry. Employing a quasi-experimental design, the study involved two experimental classes and two control classes. Each group participated in pretests and posttests to assess their chemical literacy and scientific attitudes. The analysis revealed that the PBL-STEM model significantly enhanced students' chemical literacy (N-Gain = 0.54) and scientific attitudes (N-Gain = 0.46) compared to traditional learning methods. Although the improvement in scientific attitudes was more pronounced, the increase in chemical literacy was relatively lower, indicating the necessity for adjustments in instructional approaches to deepen students' understanding of chemical concepts. The integration of green chemistry principles within the PBL-STEM model effectively connected chemistry education with global environmental challenges while also fostering 21st-century skills such as critical thinking and problem-solving. This study concludes that the PBL-STEM model presents a promising alternative for enhancing the quality of chemistry education and preparing students to navigate the complexities of an ever-evolving world.

Keywords: Chemical literacy; Green chemistry; Problem-based learning; Scientific Attitudes; STEM

Introduction

The rapid advancement of science and technology, particularly with the emergence of Industry 4.0, has transformed various sectors, including education, necessitating a change in how students engage with learning (Liao et al., 2018; Afrianto, 2018). In this context, chemistry education must evolve to foster a 21st-century learning environment where students actively seek out their own resources and develop essential cognitive skills such as problem-solving, critical thinking, communication, teamwork, and creativity (Wulandari et al., 2022; Ismail et al., 2023). Despite the emphasis on these competencies, many students continue to struggle with applying chemical concepts to real-world problems, which hampers their problem-solving and critical thinking abilities. To address this issue, STEM-integrated Problem-Based Learning (PBL) offers an effective approach by combining science, technology, engineering, and mathematics to create a more interactive, collaborative, and contextual learning environment. This model encourages students to apply chemical concepts to practical scenarios, fostering a

How to Cite:
Tairas, N., Rohaeti, E., Prodjosantoso, A. K., Ikhsan, J., & Ningthias, D. P. STEM-Integrated Problem-Based Learning in Green Chemistry to Enhance Chemical Literacy and Scientific Attitudes. *Jurnal Penelitian Pendidikan IPA*, *11*(3), 615-626. https://doi.org/10.29303/jppipa.v11i3.10666

deeper understanding and refining essential skills that prepare them for the challenges of the modern world (Rosiningtias et al., 2023). Thus, the transformation driven by Industry 4.0 requires a more holistic, student-centered approach to chemistry education that not only imparts knowledge but also cultivates critical competencies necessary for success in an increasingly complex, interconnected global society.

Putra (2022) reports that grade XII students exhibit a relatively low level of green chemistry literacy, with an average score of only 58%. While a small portion of students carefully engage with the material, many struggle to comprehend the content. Most students are unfamiliar with green chemistry concepts, largely due to weak literacy in the subject, which results in low knowledge retention. Further studies indicate that environmental green chemistry has been successfully integrated into microscopic scale experiments (Listyarini et al., 2019; Ratnasari et al., 2019). Furthermore, Fauziyah et al. (2019) demonstrate the effective integration of green demonstrate the effective integration of green chemistry practicum within a problem-based learning (PBL) framework.

In chemistry education, several factors contribute to students' learning challenges. Chemical concepts, often abstract, are difficult for students to grasp, particularly when it comes to applying them in real-life contexts. Students frequently struggle to understand chemical theories, lack motivation to engage with the material, and perceive chemistry as a difficult subject (Suswati, 2021). Moreover, Priliyanti et al. (2021) highlight that such learning difficulties are common across various schools. The overreliance on conventional teaching methods further exacerbates these challenges, leading to subpar learning outcomes (Erlina et al., 2019; Jamilah et al., 2021).

Given the complexity of the 21st-century competencies that students are expected to master, addressing these challenges in chemistry education is (Mukaromah et al., 2022). According to McFarlane, (2013), mastering 21st-century skills requires complex interdisciplinary learning that connects knowledge to real-world problems. One promising approach is the implementation of instructional models that foster such interdisciplinary integration (Muhali, 2019). The STEM (Science, Technology, Engineering, and Mathematics) approach is particularly effective in nurturing these competencies (Diana et al., 2021). Research demonstrates that STEM education fosters critical thinking skills (Akcanca, 2020) and encourages students to tackle real-world challenges using the combined lenses of science, technology, engineering, and mathematics (Bybee et al., 2006). Additionally, the integrative nature of STEM allows it to complement various teaching models, enhancing its applicability across diverse learning environments (Davidi et al., 2021).

A key pedagogical model that aligns well with STEM is Problem-Based Learning (PBL). PBL is an active learning approach that emphasizes student-centered exploration of real-world problems, facilitating the construction of knowledge in meaningful contexts (Arends, 2014). PBL has been shown to enhance higher-order thinking skills, which are crucial for solving complex, contextual challenges (Fajrilia et al., 2019). When integrated with STEM, PBL not only improves learning outcomes (Roektiningroem & Cahyaningsih, 2018; Maulidia et al., 2019; Ningsih, 2020) but also fosters critical thinking (Ariyatun & Octavianelis, 2020; Roektiningroem & Cahyaningsih, 2018), enhance science literacy, and develop positive student character (Putri et al., 2020). Furthermore, Arisoy et al. (2021) emphasize that practicing critical thinking within specific disciplines significantly strengthens students' overall critical thinking abilities.

The relevance of green chemistry in modern education cannot be overstated. Green chemistry is instrumental in reducing or eliminating the use and production of hazardous substances, offering numerous environmental and health benefits (McMurry, 2013; Koulougliotis et al., 2021). It plays a central role in minimizing hazardous waste, promoting safer synthesis methods (Al Idrus et al., 2021), conserving energy, and supporting the Sustainable Development Goals (Armstrong et al., 2019; Anastas & Zimmerman, 2018). Moreover, green chemistry helps reduce chemical accidents, such as fires, explosions, and exposure incidents (Sharma & Mudhoo, 2010). Its 12 principles provide a comprehensive framework for reducing waste, improving safety, and advancing sustainable practices in various industries.

Green chemistry is already being applied in innovative ways in everyday life, such as waterless washing (Rathi et al., 2023), environmentally friendly paints, and biodegradable plastics. Additionally, green chemistry principles contribute to advancements in clean water production, green technology in construction, and even in the development of medicines with fewer harmful side effects (Saini, 2018; Kaul, 2017; Jean et al., 2015). Given the widespread importance of green chemistry, integrating it into educational practices is crucial.

Despite the existing body of research on STEM and PBL, particularly their application in science education, there remains a notable gap in the application of these methods in chemistry education to improve students' chemical literacy and scientific attitudes. For instance, while previous studies (Widiyatmoko & Darmawan 2023; Suciana et al., 2023) have explored the impact of

STEM-PBL integration on critical thinking and learning outcomes, few have focused specifically on the enhancement of chemical literacy and scientific attitudes in the context of green chemistry. This gap presents a significant opportunity for further exploration.

The findings from previous research indicate that PBL integrated with STEM can enhance critical thinking skills (Ariyatun & Octavianelis, 2020; Febrianto et al., 2021; Mustofa et al., 2021; Rohmah et al., 2021) and improve student learning outcomes (Ariyatun & Octavianelis, 2020; Nurazmi & Bancong, 2021). However, the application of PBL alongside STEM methods in chemistry classes, specifically to enhance students' chemical literacy and scientific attitudes, has not been widely studied.

This study aims to fill this gap by evaluating the impact of integrating STEM and PBL in chemistry education, with a focus on improving students' chemical literacy and scientific attitudes. By using green chemistry materials, the research will implement a STEM-integrated PBL approach as an alternative to traditional chemistry instruction. This approach promises to not only improve learning outcomes but also foster critical thinking, scientific attitudes, and a deeper understanding of green chemistry among students.

The steps involved in the STEM-integrated PBL process include guiding students to identify problems, structuring their learning experiences, facilitating both individual and group learning, developing and presenting solutions, and analyzing the integrated problem-solving process. This approach will incorporate real-world problem-solving that integrates science, technology, engineering, and mathematics to enhance chemical literacy and foster positive scientific attitudes.

In light of these considerations, the present study seeks to determine whether there is a significant difference in chemical literacy skills and scientific attitudes between students taught using the STEM-integrated PBL model and those taught using a direct learning model based on a scientific approach to green chemistry. This research is vital as it explores innovative teaching methods that could significantly improve both the quality of chemistry education and students' engagement with the subject.

Method

This study employed a quasi-experimental technique. The research model followed nonequivalent with a pretest-posttest control group design, which included two experimental groups and two control groups, each participating in both a pretest and a posttest. The experimental group comprised students from SMA Negeri 4 Pare-Pare who engaged in Problem-Based Learning (PBL) integrated with STEM, while the control group consisted of students from a different class who followed verification learning model. Both groups underwent pretests and posttests to evaluate their chemical literacy skills and scientific attitudes. The research design is detailed in Table 1.

Participants in this study were students from State Senior High School 4 in Pare-Pare City. The research involved two experimental classes: X1 with 28 students and X2 with 30 students, totaling 58 students. Additionally, two control classes were included: X3 with 31 students and X4 with 27 students, resulting in the same total of 58 students for the control group. The research sample was selected using a random sampling approach (Fraenkel et al., 2009). The study was conducted at State Senior High School 4 Pare-Pare from October 14 to November 1, 2024, as detailed in Table 2.

Table 1. Research Design

Experimental class	O1	X1	O3
Control class	O2	X2	O4

Note: O1 = pretest of experimental class; O2 = pretest of control class; X1 = PBL integrated with STEM; X2 = verification learning model O3 = posttest of experimental class; O4 = posttest of control class

Table 2. Research Time Research

Meeting	Week	Activity
1	I	Pretest (1 jp) – learning process (2 jp)
2	II	Learning process (2 jp) – practice questions (1 jp)
3	III	Learning process (2jp) – posttest (1jp)

The selection of research samples was carried out using simple random sampling techniques (Fraenkel, Jack R., Wallen, 2009). The chemical literacy test questions were arranged based on 3 (three) aspects include: a) chemical content, b) chemical context, and c) high-level thinking skills. These test questions included material on green chemistry. The theoretical validity was confirmed by two experts in green chemistry, while empirical validity was established by testing 36 students from class XI IPA at SMAN 2 Pare-Pare. This process resulted in 14 validated chemical literacy questions, as shown in Table 3, and 20 scientific attitude questionnaires, which were structured around four aspects: curiosity, openness, objectivity, and critical attitudes. These questionnaires utilized a Likert scale (1-5), as detailed in Table 4. The trial results were analyzed using the product moment correlation (rxy) method with SPSS software. The empirical validity of the instrument items is indicated by an rxy value greater than the rtable. An instrument is considered valid if the validity estimate exceeds 0.339 (Hair et al., 2013).

Reliability testing was conducted using the same test subjects, based on the Cronbach's alpha coefficient (ri). The output from the SPSS program provides estimated reliability for the instrument items. An instrument is considered reliable if the reliability estimate exceeds 0.60 (Hair et al., 2013). In this study, the reliability of the instrument was confirmed with 14 chemical literacy questions related to green chemistry, yielding an ri value of 0.854, and 20 statements from the scientific attitude questionnaire, which had an ri value of 0.855.

To evaluate the research hypothesis for acceptance or rejection, the decision criteria state that if the statistical test results indicate a significance level of less than 0.05, H1 will be rejected and H2 will be accepted. The dependent variables in this study are chemical literacy and scientific attitude. Therefore, the product trial data were analyzed using the MANOVA (multivariate analysis of variance) method, utilizing N-Gain data.

Table 3. Chemical Literacy Ability Validation Results

No. Question	rxy value	Information	No. Question	rxy value	Information
1	-0.224	Not valid	16	0.427	Valid
2	0.499	Valid	17	0.344	Valid
3	-0.124	Not valid	18	0.238	Not valid
4	0.301	Not valid	19	0.575	Valid
5	0.613	Valid	20	0.529	Valid
6	-0.005	Not valid	21	0.616	Valid
7	-0.103	Not valid	22	0.212	Not valid
8	0.521	Valid	23	0.659	Valid
9	-0.126	Not valid	24	0.488	Valid
10	0.267	Not valid	25	0.479	Valid
11	0.319	Not valid	26	0.488	Valid
12	0.158	Not valid	27	0.107	Not valid
13	0.520	Valid	28	0.122	Not valid
14	0.160	Not valid	29	-0.118	Not valid
15	0.411	Valid	30	0.016	Not valid

Table 4. Results of Scientific Attitude Validation

No. Question	rxy value	Information	No. Question	rxy value	Information
1	0.496	Valid	16	0.380	Valid
2	0.158	Not valid	17	0.398	Valid
3	0.210	Not valid	18	0.348	Valid
4	0.047	Not valid	19	0.230	Not valid
5	0.428	Valid	20	0.214	Not valid
6	0.699	Valid	21	-0.004	Not valid
7	0.507	Valid	22	0.637	Valid
8	0.440	Valid	23	0.614	Valid
9	0.309	Not valid	24	0.649	Valid
10	-0.365	Not valid	25	0.601	Valid
11	0.280	Not valid	26	0.504	Valid
12	0.447	Valid	27	0.721	Valid
13	0.450	Valid	28	0.483	Valid
14	0.417	Valid	29	0.216	Not Valid
15	0.448	Valid	30	0.495	Valid

Result and Discussion

Implementation of STEM-Integrated PBL Model

An experimental class that received PBL-STEM-based learning and a control class that followed a scientific approach. Both groups participated in three sessions, which included a pretest, main learning activities, and a posttest. Throughout these sessions, the teacher acted as a facilitator, guiding discussions, exploring concepts, and overseeing group presentations to support students' understanding of green chemistry concepts.

During the Problem Orientation stage (Figure 1), the teacher presents a stimulus, such as a thought-provoking question, video, or a real-life case study, to motivate students to think critically, identify problems, and determine aspects that require further investigation. Research by Niswa et al. (2022) show Problem-Based

Learning (PBL) can improve students' critical thinking skills outcomes, with an average increase in classical critical thinking skills of 67.5 in the first cycle and 76.35 in the second cycle. Once the problem is understood, students are divided into small groups of 3-5 members during the Group Formation and Learning Resources Exploration stage. In these groups, they collaborate to devise problem-solving strategies by utilizing various learning resources, including e-books, instructional videos, and scientific journals accessed through digital devices. This process broadens students' perspectives, enhances information-based problem-solving capabilities, and improves their collaborative skills during discussions.

After gathering information from multiple sources, students proceed to the STEM Concept Discussion and Analysis stage, where they analyze the problem by identifying the components of Science, Technology, Engineering, and Mathematics in the context of green chemistry. For instance, they might investigate the use of environmentally friendly chemicals or the application of photocatalysts in industrial settings. This discussion aims to develop their problem-solving skills and encourage critical thinking that connects various disciplines. Each group then presents their findings during the Scientific Presentation and Argumentation stage, where they share their results and receive feedback from other groups. This process enhances their scientific communication skills and fosters an openness to diverse perspectives.

The final stage of this lesson is Reflection and Evaluation, where students reflect on the concepts they have learned and their applications in everyday life, as shown in Figure 2. The teacher provides feedback on the results of discussions and presentations, and conducts an evaluation using a post-test to assess students' understanding of chemical literacy and their scientific attitudes. This evaluation focuses not only on knowledge improvement but also on the development of students' critical thinking skills and collaboration abilities. Through this reflection, students have the opportunity to contemplate their learning experiences and connect the knowledge gained to practical applications in real life, thus enhancing their awareness of the importance of STEM-based learning in understanding the scientific phenomena around them.

Differences in Chemical Literacy Skills and Scientific Attitudes Between Experimental and Control Groups

The statistical analysis began with prerequisite tests to assess the homogeneity and normality of the samples. The results of the MANOVA prerequisite test indicated that nine conditions were met, allowing for the continuation to the MANOVA test. The results of Hotelling's Trace multivariate test showed a significance level of Sig. = 0.01, which is below the 0.05 threshold. This finding indicates significant variation in chemical literacy and scientific attitude across courses. Specifically, it suggests that students taught using the PBL-STEM paradigm exhibited greater chemical literacy skills and scientific attitudes than those taught with the traditional scientific method.

These results align with the findings of Gultom et al. (2024), Deti Ratih et al. (2024), and Johan et al. (2024), which demonstrated that the problem-based learning (PBL)-STEM model significantly enhances students' chemical problem-solving skills, as participants in this model were trained to analyze issues relevant to their own contexts. Additionally, Rohaeti et al. (2020) found that collaborative student inquiry in Project-Based Learning (PBL) improved students' scientific attitudes. The findings of this study are consistent with Prastika et al. (2022), which also indicated that the use of PBL-STEM improved student learning outcomes. This study concludes that the integration of the PBL paradigm with STEM enables students to analyze contextual challenges, thereby enhancing their problem-solving abilities and boosting their confidence.

Differences in Chemical Literacy Skills Between Experimental and Control Groups

The average N-Gain of the control class was 0.48, while the experimental class, which was taught using the STEM-integrated PBL paradigm, achieved an average N-Gain of over 0.54, as shown in Table 5.

The STEM-integrated PBL model enhances learning by incorporating real-life examples, allowing students to relate to familiar phenomena. Research by Fikriana et al. (2023) explain this STEM approach has also improved their ability to explain and investigate issues related to these phenomena. Additionally, STEM-integrated PBL aids learners in identifying the components present in the studied phenomenon (Devi et al., 2024). Unlike the scientific method, which may sometimes lack relevance to students' everyday experiences, PBL connects learning to real-world contexts.

Table 5. Manova Statistical Description

	Model Bel.	Mean	Std. Deviation	N
N-Gain Chemical Literacy	PBL STEM	.5435	.30122	57
	Sacientific	.4772	.25129	57
	Total	.5104	.27815	114
N-Gain Scientific Attitude	PBL STEM	.4568	.31379	57
	Scientific	.2772	.32315	57
	Total	.3670	.32967	114

This aligns with Walsh's theory presented in Symposium et al. (2007), which posits that PBL enhances positive attitudes and develops problem-solving skills.

Other sources also suggest that PBL boosts motivation and problem-solving abilities while fostering an understanding of cause and effect (Hallinger, 2021; Barrows & Tamblyn, 1980). Furthermore, research by Baptista et al. (2023) indicates that the STEM approach can enrich the complexity of students' cognitive structures. Thus, these insights collectively suggest that STEM-integrated PBL enhances problem-solving abilities, cognitive complexity, and motivation, ultimately improving students' chemical literacy and scientific attitudes.

Table 6. Percentage of Students' Chemical Literacy Skills

Indicator	Question Number	% mean Experiment Group	% mean Control Group
Content	1, 2, 3, 4	40%	46%
HOLS	5, 6, 7, 8, 13, 14	28%	25%
Context	9, 10, 11, 12	32%	29%

Table 6 shows that Indicator 1, which covers understanding of basic chemistry content, is the dimension most mastered by students, while Indicator 3, which relates to higher order learning skills (HOLS) and context application, shows lower understanding in both experimental and control groups. This can be explained by the nature of Indicator 1 content which is more concrete and directly related to chemistry materials commonly taught in the classroom. With the PBL-STEM approach, students are given the opportunity to connect theory with practical applications in the real world, which strengthens their understanding of basic concepts (Smith et al., 2022). In contrast, Indicator 3, which involves analysing contextual problems and applying concepts in real situations, is more difficult to understand as it requires more extensive reference searches and in-depth understanding. According to Gusman et al. (2023), although the PBL-STEM model motivates students to think critically, the main challenge lies in students' difficulty in formulating more complex analytical and critical thinking-based solutions.

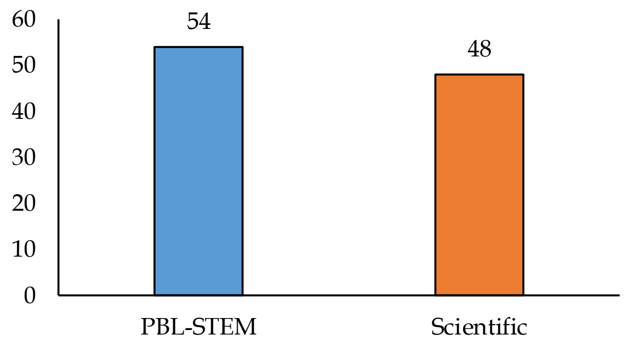

Figure 1. Comparison of chemical literacy skills

Indicator 3 shows lower understanding, but the application of PBL-STEM-based learning still contributes positively to the overall improvement of chemical literacy. Real problem-based learning and higher-order thinking require extra effort in providing in-depth and contextualised materials that can encourage students to think more critically. Research by Wan et al. (2022) shows that PBL-STEM requires a more structured approach, such as providing real case examples and relevant challenges. Thus, to improve mastery of Indicator 3, there needs to be an increase in assisting students in integrating theoretical knowledge with real-world phenomena more thoroughly.

Differences in Scientific Attitude between Experimental and Control Groups

The scientific attitude of students taught using the STEM-integrated PBL learning technique was 0.46, compared to 0.28 for those instructed through traditional scientific methods. This finding aligns with the research of Adisha et al. (2024) and Setiawaty et al. (2018), which showed that the PBL-STEM model significantly enhances students' scientific attitudes. Table 7 provides data on students' scientific attitudes within the context of the STEM-integrated PBL model.

Table 7. Percentage of Students's Scientific Attitudes

Indicators	Question number	% mean experiment group	% mean control group
Curiosity	1 – 5	27%	27%
Open Minded	6 – 7	23%	23%
Objectivity	8 – 14	26%	26%
Critical Attitude	15 – 20	24%	24%

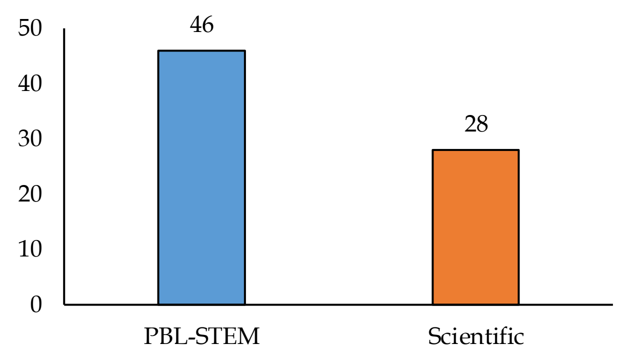

Figure 2. Comparison of scientific attitude

PBL also makes The ease and interest that students experience when engaging with chemical concepts fosters enthusiasm and deep curiosity. This engagement positively affected their overall scientific attitude, as reflected in their posttest scores (Wahyudiati, 2022). Learners become more critical when addressing questions related to topics covered in lessons. An objective approach to the posttest questionnaire boosts their confidence, thereby enhancing their scientific outlook. However, the dimension of scientific mindset most lacking among students is open-mindedness, indicating that they remain uncertain about expressing views that challenge established expectations. Figure 4 compares the scientific attitudes of the control and experimental classes. The experimental class demonstrated superior mastery of the four scientific attitude indices compared to the control class. Notably, the indicator for open-mindedness received the lowest score in both classes using the STEM-integrated PBL learning paradigm.

Effective Contribution of STEM-integrated PBL Application to Chemical Literacy and Scientific Attitudes

This analysis aimed to evaluate the effectiveness of the PBL-STEM model in enhancing both chemical literacy and scientific attitudes. The findings indicate that this model significantly contributes to improvements in both areas, as well as in the development of critical thinking skills. A contribution of 7.9% (categorized as high/strong on Cohen's scale) suggests that the PBL-STEM model has a notable positive impact on enhancing students' chemical literacy and scientific attitudes simultaneously. Previous research has shown that PBL can enhance students' communication skills, particularly in asking questions, articulating views, and sharing discussion results (Langitasari et al., 2021).

The effectiveness of PBL-STEM in improving chemical literacy and scientific attitudes can be attributed to the nature of project-based learning, which engages students in solving contextual problems relevant to their lives, making the learning experience more meaningful and engaging. This approach not only helps student’s master theoretical concepts but also enables them to apply chemical principles in real-world situations, thereby strengthening their cognitive and affective skills. Research by Sumartati (2020) further supports this by demonstrating that STEM education can enhance critical thinking and innovation, as students encounter challenges that necessitate a multidisciplinary approach. Through the integration of various disciplines, students learn to solve problems in a more structured and effective manner.

Consequently, the implementation of PBL-STEM positively affects learning outcomes, including students' cognitive abilities and attitudes (Nur & Ikhsan, 2024; Kartamiharja et al., 2020). The results of this study demonstrate that STEM-integrated PBL enhances students' chemical literacy and scientific attitudes. This improvement arises from the contextual problem analysis activities inherent in STEM-integrated PBL, which develop students' analytical skills across the STEM domains, effectively advancing their cognitive and affective dimensions.

Effectiveness of STEM-integrated PBL on Chemical Literacy Skills

The application of learning models to chemical literacy skills yielded a significance value of 0.205, which exceeds the threshold of 0.05. This indicates that no significant difference was found in the chemical literacy skills of students taught using two different learning models. This result suggests that the hypothesis of a significant impact on chemical literacy between the two models cannot be supported, meaning that both the STEM-integrated PBL model and the traditional scientific approach produced similar outcomes in this regard. A similar analysis applies to the impact of STEM methods on students' problem-solving abilities (Yildirim, 2016).

The lack of significant difference in chemical literacy skills between the two learning models can be attributed to several factors. One possibility is that both models PBL-STEM and the traditional scientific approach may have effectively addressed the foundational concepts of chemistry, albeit in different ways. While PBL-STEM engages students with real-world problems, it may not have sufficiently deepened their understanding of chemical concepts compared to the traditional approach, which often emphasizes direct content delivery. Furthermore, the findings from Afikah et al. (2023) regarding higher-order thinking skills (HOTS) and student collaboration in chemistry did not reveal any significant differences. Additionally, research conducted by Lestari et al. (2018) indicated that the effective contribution of the medium category to the science process skills of STEM classes is equivalent to the effective contribution of chemical literacy skills in this study, which was only 1.4% (classified as medium/medium on the Cohen scale).

Another explanation could be the nature of the chemical literacy test itself, which may not have fully captured the nuances of the skills promoted by the STEM-integrated PBL model. If the test effectively assesses students' skills, it is likely to demonstrate a significant impact from the implementation of PBL-STEM. Research by Parno et al. (2019) indicates that students' problem-solving skills in classes using PBL-STEM showed a notable medium-range impact. Additionally, it is important to recognize that chemical literacy encompasses not only mastery of content but also the application of concepts in various contexts. Traditional approaches may have provided sufficient opportunities for students to develop these aspects as well.

Effectiveness of STEM-integrated PBL on Scientific Attitude

The impact of learning models on scientific attitudes was found to be statistically significant, with a p-value of 0.003, which is less than the threshold of 0.05. This indicates that there is a clear difference in the scientific attitudes of students when taught using two different learning models, with the STEM-integrated PBL approach leading to a more positive outcome. The effective contribution of the STEM-integrated PBL model to improving scientific attitudes was measured at 7.5%, which is categorized as high according to Cohen's scale. This finding supports the idea that the PBL-STEM model is highly effective in enhancing students' scientific perspectives. The significant improvement in students' scientific attitudes can be attributed to several factors inherent in the PBL-STEM approach. First, this model actively engages students in solving real-world problems, encouraging them to think critically, collaborate, and communicate effectively. As students work through authentic challenges, they are not only applying their scientific knowledge but also developing a more open and reflective attitude toward science. Previous studies, such as those by Yildirim (2016) and Khotimah et al. (2021), have also indicated that STEM-integrated PBL positively influences students' scientific attitudes by fostering critical thinking, creativity, and a deeper engagement with scientific concepts. Consequently, these results suggest that the application of STEM-integrated PBL is a robust strategy for improving students' scientific attitudes, especially in terms of fostering curiosity, objectivity, and critical analysis in scientific contexts.

Additionally, the interdisciplinary nature of STEM learning encourages students to connect various scientific disciplines, which can lead to a more comprehensive and well-rounded understanding of scientific concepts. This holistic approach helps students see the relevance of science in everyday life, enhancing their scientific curiosity and motivation (Adhelacahya et al., 2023). Moreover, the collaborative and problem-solving environment created in PBL-STEM classrooms fosters a sense of ownership and responsibility in students, which further contributes to the development of positive scientific attitudes. These factors collectively explain why the STEM-integrated PBL model was able to produce a significant and high-impact contribution to students' scientific attitudes, as reflected in the 7.5% effective contribution measured in the study.

Conclusion

This study demonstrates that integrating STEM with the Problem-Based Learning (PBL) model significantly enhances students' chemical literacy and scientific attitudes. The experimental group employing the STEM-PBL approach exhibited notable improvements in chemical literacy (N-Gain = 0.54) and scientific attitudes (N-Gain = 0.46) compared to the control group that used traditional teaching methods. This indicates that STEM-PBL not only enhances understanding of green chemistry concepts but also fosters essential 21st-century skills such as critical thinking, collaboration, and problem-solving.

While an improvement in chemical literacy was observed, the increase in scientific attitudes was more pronounced. This difference suggests that, although the STEM-PBL model effectively motivates students to tackle real-world problems, further customization is necessary to deepen their understanding of chemistry concepts, particularly those that require higher-order thinking skills (HOTS). The integration of green chemistry principles within this model has proven effective in aligning chemistry education with sustainable development goals. Overall, the STEM-PBL model presents a promising alternative to traditional chemistry education, promoting both cognitive and affective development in students and equipping them to meet the challenges of the modern world.

Acknowledgments
Thanks to all parties who have supported the implementation of this research. I hope this research can be useful.

Author Contributions
N. T. conducted research at Senior High School 4 Pare-Pare and drafted the article; E. R. and J. I guided and reviewed the manuscript; A. K. P validated the instrument; D. P. N reviewed and revised the manuscript. All authors have read and approved the published version of the manuscript.

Funding
This research was independently funded by researchers.

Conflicts of Interest
The authors declare no conflict of interest.

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