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LITERACY AND RESEARCH-ORIENTED COOPERATIVE PROBLEM-BASED LEARNING MODEL: BRIDGING STUDENTS' CHEMICAL LITERACY TO SUPPORT SUSTAINABLE EDUCATION

F. I. Pratama*[1], E. Rohaeti[1], E. W. Laksono[1], R. Joronavalona[2]

[1]Chemistry Education Department, Universitas Negeri Yogyakarta, Indonesia
[2]University of Antananarivo, Madagascar

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ABSTRACT

Sustainable education can be achieved through an innovative learning process, and one way to do so is to use a high-quality learning model. Literacy and Research-Oriented Cooperative Problem-Based Learning (LIRACLE) is a new learning model developed for undergraduate learning. LIRACLE is adapted from Problem-based learning, cooperative learning, research learning, and literacy-oriented learning. This study aims to examine the effect of the LIRACLE learning model on undergraduate students' chemical literacy. The research employed a quasi-experimental, post-test-only control-group design with undergraduate chemistry students. The instrument used is a chemical literacy rubric. The data were analyzed using an independent-samples t-test. The result of the independent sample t-test is the Asymp. Sig. (2-tailed) of 0.000. This result is below 0.05, indicating a significant difference between the groups using the LIRACLE and PBL learning models in chemical literacy skills. These findings indicate that the LIRACLE learning model significantly improves undergraduate students' chemical literacy compared to the PBL model. Therefore, LIRACLE has the potential to support the development of students' chemical literacy in undergraduate learning.

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Keywords: chemical literacy; LIRACLE model; sustainable education

INTRODUCTION

The development of science and technology has brought the world into an era of disruption. The era of disruption has become a reality that the world community, including Indonesia, must face (Fitriyana et al., 2020; Pratama et al., 2025). The impact of this era has made Indonesia's young generation more qualified and able to compete globally to meet the demands of success in the workplace and the future (Edwards et al., 2023). In the context of education, this transformation requires implementing sustainable education systems that prepare learners with the competencies needed to address complex global challenges. Sustainable education emphasizes the development of critical thinking, literacy, collaboration, and problem-solving skills that enable students to actively participate in building a sustainable future (Pratama et al., 2024; Alenka & Iztok, 2025; Sari et al., 2025).

The quality of a country's young generation can be seen in the quality of its undergraduate students (Mulyopratikno & Wiyarsi, 2025; Myktybekova et al., 2025). This is based on the age range of undergraduate students, who are generally aged 18–23. Therefore, efforts must be made to develop students' abilities by providing the best quality education possible (Pratama et al., 2024). However, research from the Program for the International Assessment of Adult Competencies (PIAAC) in 2016 also showed that students re-

***Correspondence Address**
E-mail: faiz0021fmipa.2023@student.uny.ac.id

mained very weak in literacy and problem-solving (Hämäläinen et al., 2017). The results from PIAAC show that 70% of respondents from Indonesia have literacy skills at level 1 and below, indicating that the young generation of Indonesia is only able to read short texts on topics that are familiar to them and are only able to capture one message or information from the text (Keslair & Paccagnella, 2020). Therefore, based on the weak literacy and problem-solving abilities of Indonesia's young generation, we can conclude that their literacy skills are also at an unsatisfactory level (Cervetti & Wright, 2020).

Problem-based learning (PBL) offers an alternative approach to developing literacy, including chemical literacy, by integrating science into a real-life case (Akcay & Benek, 2024). This is because the primary goal of PBL is to encourage students to be active and to enhance the development of their abilities (Brilingaite et al., 2018). PBL also influences life career skills (Nurtanto et al., 2020). In addition to its benefits, the PBL approach also has its own demerits. PBL requires a lot of time if students are used to depending on the lecturer to provide material (Almulla, 2020). This will also be worse if the students are not enthusiastic about learning.

However, various findings indicate that students' chemical literacy remains at a low to moderate level, particularly in applying concepts, engaging in scientific reasoning, and interpreting scientific data. This situation indicates that conventional learning and learning models that have not been comprehensively integrated with literacy and research are not fully capable of meeting the demands of continuing education. Therefore, innovative learning models that can systematically integrate literacy, research, collaboration, and problem-solving are needed (Wiyarsi et al., 2021; Rahmawati et al., 2024).

Modifications to the PBL model can increase student enthusiasm for learning, and several approaches can be used to build it. One example is providing a literacy approach through discourse on problems in everyday life (Guerrero & Torres-Olave, 2021). Another approach is a research approach. Literacy and research-based learning activities have been proven to increase student enthusiasm for learning (Evans et al., 2017; Comillo & Mistades, 2025). If students are enthusiastic about learning, they will be more likely to understand concepts (Frensley et al., 2020). This shows that there is a link between enthusiasm for learning and conceptual understanding. This PBL modification brings innovation in the development of learning models. In the context of undergraduate chemistry learning, innovation must be implemented to prepare students to become future professional teachers (Easa & Blonder, 2024). However, there has been little development in learning models focused on adult learning.

One example is the Research-Oriented Collaborative Inquiry Learning Model (REORCILEA) developed by Rohaeti et al. (2020). However, this model mainly focuses on improving students' critical thinking, scientific attitudes, and science process skills (Irwanto, 2022, 2023). Therefore, the Literacy and Research-Oriented Cooperative Problem-Based Learning (LIRACLE) model is proposed to enhance students' chemical literacy specifically.

The LIRACLE (Literacy and Research-Oriented Cooperative Problem-Based Learning) learning model was developed to be an innovation. LIRACLE was developed specifically to improve students' chemical literacy, cultivate scientific thinking, enhance scientific reasoning skills, stimulate cooperation, and familiarize students with research and inquiry. Currently, LIRACLE is still in development and requires six syntaxes to be executed sequentially. These six syntaxes are combined with the concept of adsorption chemistry to create a learning environment oriented towards literacy and research to solve every day-life problems cooperatively (Pratama et al., 2024, 2025). These skills include initiating problems, conducting investigations, integrating conceptual understanding with problem-solving, designing experiments, writing a scientific paper, and communicating. The result of this model is a scientific article that is assessed by the chemical literacy rubric.

The LIRACLE learning model is theoretically grounded in several major learning theories, including constructivism, progressivism, and pragmatism. In addition, LIRACLE integrates Problem-based Learning, cooperative learning, literacy-oriented learning, and research-oriented inquiry learning. LIRACLE is a systematic, methodological, and consistent investigation effort based on problems that occur in everyday life, using experiments in chemistry laboratories, from designing experiments to solve existing problems, conducting experiments, writing scientific papers, and systematically communicating research results and integrative outcomes (Pratama et al., 2025). Laboratory support will help students develop their chemical literacy skills (Li et al., 2024). However, the LIRACLE learning model needs to be empirically tested for its effectiveness. The chemical material in this research is an adsorption material. This is based on the many problems in everyday life related to adsorption (Maryanti et al., 2020). Adsorption is widely applied in environmental technologies such as water purification, waste treatment, and pollution control. Therefore, learning about adsorption provides an opportunity for students to connect chemical concepts with real-world environmental issues, an important aspect of sustainable education. (Rathi & Kumar, 2021; Hassan et al., 2023). However, many adsorption materials are abstract. The examples are the Langmuir and the Freundlich isotherms (Stawiński et al., 2017).

Regarding the curriculum structure in Indonesia, adsorption is included in university-level materials but has not been taught at previous levels of education. This causes the adsorption material to require students' high-level thinking skills. Based on the adsorption material's characteristics, the author chose adsorption as the research method.

Despite the potential of problem-based learning to promote active learning, previous studies indicate that students' chemical literacy remains at a low to moderate level (Fareza et al., 2024). Existing learning models have not fully integrated literacy activities, collaborative learning, and research-based inquiry in a systematic way, particularly in undergraduate chemistry education. Consequently, there is a need for an innovative learning model that can effectively integrate these components to improve students' chemical literacy.

Given the urgency, preliminary studies, and analysis gaps, this study is limited to examining the effect of the LIRACLE learning model on students' chemical literacy in undergraduate education. In this study, chemical literacy is operationally defined as students' ability to: (1) understand and explain chemical concepts, (2) apply chemical knowledge to contextual scientific problems, (3) interpret chemical representations and scientific data, and (4) construct evidence-based arguments related to chemical phenomena (Kohen et al., 2020; Cigdemoglu et al., 2017). The study does not address all aspects of learning outcomes; rather, it specifically focuses on chemical literacy skills. The purpose of this study is to examine the effectiveness of the LIRACLE learning model in influencing students' chemical literacy towards adsorption materials. The LIRACLE model will be compared with the PBL model. Therefore, the research question addressed in this study is: Does the Literacy and Research-Oriented Cooperative Problem-Based Learning (LIRACLE) model significantly affect undergraduate students' chemical literacy compared to the Problem-Based Learning (PBL) model?

This study contributes to chemistry education research by providing empirical evidence on the effectiveness of the Literacy and Research-Oriented Cooperative Problem-Based Learning (LIRACLE) model in improving undergraduate students' chemical literacy. Furthermore, integrating literacy-oriented activities, cooperative learning, and research-based inquiry within the LIRACLE model offers a novel instructional framework for chemistry learning in higher education. The competencies developed through this model align with the principles of sustainable education and support the objectives of Sustainable Development Goal 4 (Quality Education), which emphasizes improving the quality of learning to prepare future generations to address global challenges.

METHODS

This study employed a quasi-experimental post-test-only control-group design. This design allows researchers to examine the effect of an instructional treatment under authentic classroom conditions without fully randomizing participants (Gribbons & Herman, 1996). It is widely used in educational research to evaluate the effectiveness of instructional interventions (Creswell, 2018).

In this design, participants were divided into two groups: an experimental group and a control group. The experimental group was taught using the Literacy and Research-Oriented Cooperative Problem-Based Learning (LIRACLE) model, while the control group was taught using the Problem-Based Learning (PBL) model. The comparison between these two groups enabled the researchers to identify differences in students' chemical literacy outcomes resulting from the different learning models. Both groups participated in six face-to-face meetings, each lasting approximately 100 minutes.

The study population consisted of all third-semester undergraduate students enrolled in Chemistry Education programs in the Special Region of Yogyakarta, Indonesia. Given accessibility considerations, convenience sampling was used to select a university as the research site. The participants were 82 students, divided into two groups. The experimental group consisted of 38 students who received instruction using the LIRACLE learning model, while the control group consisted of 44 students who were taught using the PBL model. Both groups studied the same chemistry topic, namely, adsorption, during the intervention period. The differences in learning procedures between the experiment and control groups are presented in Table 1.

Table 1. The Differences in Learning Procedures

Experiment Group (LIRACLE Model)	Control Group (PBL Model)
Initiation of Problem Students were presented with contextual scientific literacy texts related to real-life adsorption phenomena (e.g., water purification and pollutant removal). At this stage, students identified problems embedded in the text through guided reading activities. This stage was designed to develop chemistry in context and initial higher-order thinking skills by applying analytical reading strategies (Moje et al., 2020).	**Orientation of the Problem** Students were introduced to a contextual problem related to adsorption phenomena.
Investigation Students worked cooperatively to investigate the identified problems by searching for relevant chemical concepts, theories, and empirical evidence from scientific references. This stage adopted inquiry-based investigation principles and emphasized analytical reasoning and evaluation of information sources, which support chemistry as knowledge and higher-order learning skills (Rohaeti et al., 2020).	**Organization** Students discussed the problem in groups, with the lecturer serving as a facilitator to guide the discussion.
Integration of Conceptual Understanding with Problem-solving At this stage, students integrated adsorption concepts (e.g., adsorption mechanisms, isotherms, and influencing factors) with problem-solving strategies. This integration aligns with problem-based learning theory, which emphasizes conceptual application rather than memorization (Barrows, 1986).	**Guiding Independent and Group Investigations** Students independently searched for relevant learning resources to understand the chemical concepts required to solve the problem.
Designing Experiment Students collaboratively designed simple adsorption experiments, including identifying variables, materials, procedures, and data-collection techniques. This stage reflects research-oriented learning, allowing students to engage in authentic scientific inquiry and strengthening their procedural understanding of chemistry.	**Group Discussion and Solution Development** Students discussed the collected information in groups and proposed solutions to the problem.
Scientific Paper Writing Students compiled their findings into a structured scientific paper comprising an abstract, introduction, methods, discussion, and conclusion. Writing scientific papers served as both a learning activity and an assessment artifact, reinforcing chemical literacy through scientific communication, argumentation, and the synthesis of evidence (Li et al., 2024).	**Evaluation** Students present their work. The lecturer facilitates the evaluation of student performance.
Communicating Each group presented its research results in a scientific discussion forum. The presentation and question-and-answer session aimed to strengthen scientific communication skills and reflective thinking, which are the core components of higher-order learning skills (Zoller & Pushkin, 2007)	

Data were collected using authentic assessment, namely, document analysis of students' scientific papers. Students' scientific manuscripts served as the primary data source to assess their chemical literacy skills. The research instrument was a chemical literacy rubric, developed based on the scientific literacy framework and adapted specifically for chemistry learning. The rubric measured three aspects of chemical literacy: Chemistry in Context, Chemistry as Knowledge, and Higher Order Learning Skills (HOLS).

Content validity of the rubric was established through expert judgment by six chemistry education experts. The experts evaluated the relevance, clarity, and representativeness of each rubric indicator. The validation process ensured that the assessment instrument aligned with the learning objectives, instructional activities, and indicators of chemical literacy. The final rubric used in this study is presented in Table 2.

Table 2. Criteria of Chemical Literacy

Assessment Section	Aspect Chemical Literacy	Criteria	Score	Indicator
Abstract	Chemistry as context	Whether or not there is a role for chemistry in the written abstract	1	Not writing the role of chemistry
			2	Writing the role of chemistry with no clear
			3	Writing the role of chemistry clearly
			4	Writing the role of chemistry very clearly and coherently
	Chemistry as knowledge	Whether or not there is draft chemistry explained in the abstract	1	Does not explain chemical concepts
			2	Explaining chemical concepts unclearly
			3	Explaining chemical concepts clearly, but not yet linking them with their role
			4	Explaining chemical concepts clearly and linking them to their role
	HOLS	The abstract is written professionally, with appropriate language.	1	The abstract is written unsystematically, but the language used is clear
			2	The abstract is written unsystematically, but the language used is clear.
			3	The abstract is written systematically, but the language is unclear.
			4	The abstract is written systematically, and the language is clear.
Background	Chemistry as context	Whether or not there is a role or impact of chemistry in the background, so that certain phenomena occur	1	Not writing the role of chemistry
			2	Writing the role of chemistry is unclear.
			3	Writing the role of chemistry quite clearly
			4	Writing the role of chemistry very clearly
	Chemistry as knowledge	Whether or not there is a chemical concept that underlies the occurrence of certain phenomena	1	Not writing chemical concepts
			2	Writing chemical concepts that underlie certain phenomena, but there are many misconceptions.
			3	Writing chemical concepts that underlie certain phenomena, but there are a few misconceptions.
			4	Writing chemical concepts that underlie certain phenomena without any misconceptions
	HOLS	The background is written in a systematic, professional manner.	1	The background is written in an unsystematic manner, and the language used is unclear.
			2	The background is written in an unsystematic way, but the language used is clear.
			3	The background is written systematically, but the language is unclear.
			4	The background is written systematically, and the language used is clear.
Method	HOLS	The method is written systematically with appropriate language selection.	1	The method is written unsystematically, and the language used is unclear.
			2	The method is written unsystematically, but the language used is clear.
			3	The method is written systematically, but the language is unclear.
			4	The method is written systematically, and the language used is clear.

Assessment Section	Aspect Chemical Literacy	Criteria	Score	Indicator
Discussion	Chemistry as context	Whether or not there is a role for chemistry in solving the problems presented	1	Not writing the role chemistry to finish the problem presented
			2	Writing the role chemistry to finish the problem with no clear
			3	Writing the role chemistry to finish the problem with enough clarity
			4	Write the role of chemistry in solving problems very clearly.
	Chemistry as knowledge	Whether or not there is draft chemistry described to finish the resulting problems	1	No chemical concepts are explained
			2	There are more than two misconceptions of chemical concepts.
			3	There is a misconception about the concept of chemistry.
			4	There are no misconceptions of chemical concepts.
	HOLS	The discussion is written systematically with appropriate language selection.	1	The discussion is written unsystematically, and the language used is unclear.
			2	The discussion is written in an unsystematic manner, but the language is clear.
			3	The discussion is well organized, but the language is unclear.
			4	The discussion is well organized, and the language is clear.
		Discussion written with sentences that make the reader think critically	1	The discussion does not make the reader think critically
			2	The discussion makes the reader little think critically
			3	The discussion makes the reader enough think critically
			4	The discussion makes the reader think critically
Conclusion	HOLS	The conclusion is written systematically with appropriate language selection.	1	The conclusion is written unsystematically, and the language used is unclear.
			2	The conclusion is written unsystematically, but the language used is clear.
			3	The conclusion is written systematically, but the language used is unclear.
			4	The conclusion is written systematically, and the language used is clear.
Presentation	HOLS	The presenter's ability to communicate the scientific content of the paper	1	The presenter does not speak to convey the content
			2	The presenter speaks less to convey content.
			3	The presenter speaks enough to convey the content.
			4	The presenter speaks to convey the content.
		The presenter's ability to answer questions	1	The presenter was not competent when answering questions.
			2	The presenter speaks less when answering questions.
			3	The presenter speaks enough when answering the questions.
			4	The presenter speaks to answer questions.

The relationship between LIRACLE syntax and chemical literacy is shown in Figure 1.

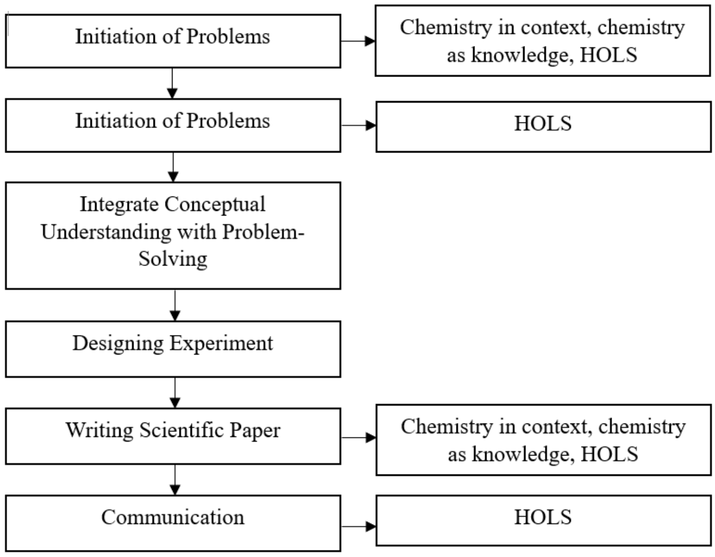

Figure 1. The Relationship of LIRACLE Syntax to Chemical Literacy

The collected data were analyzed using quantitative inferential statistics. Before hypothesis testing, assumption tests were conducted: normality test using the Shapiro–Wilk test to examine data distribution, and homogeneity test using Levene's test to examine variance equality. If both assumptions were met, an Independent Samples t-test was used to compare the chemical literacy scores of the experimental and control groups (Chicco et al., 2025). If one or both assumptions were violated, the Mann–Whitney U test was used as a non-parametric alternative (Rochon et al., 2012). All statistical analyses were conducted using SPSS software with a significance level of **α** = 0.05. The hypotheses tested were:

H_0: There is no significant difference in chemical literacy skills between students taught using LIRACLE and PBL.

H_1: There is a significant difference in chemical literacy skills between students taught using LIRACLE and PBL. This study contributes methodologically by integrating and structuring learning stages from established instructional models into an LIRACLE framework that explicitly links learning stages, research activities, and chemical literacy assessments, thereby addressing the need for research-oriented, literacy-based learning in undergraduate education.

RESULTS AND DISCUSSION

The collected student answer sheets are then assessed. Table 2 includes the score description, including the average, highest, and lowest scores.

Table 2. Students Score Result

Group	N	Mean	Std. Deviation
Experiment	38	3.529	0.1844
Control	44	3.089	0.1573

As shown in Table 2, the experimental group taught using the LIRACLE learning model obtained a higher mean chemical literacy score (M = 3.529, SD = 0.184) than the control group taught using the PBL model (M = 3.089, SD = 0.157). However, this score cannot address the hypothesis, so further statistical tests must be conducted.

Table 3. Statistical Test Results

Group	Homogeneity test (Sig.)	Normality test (Sig.)	Independent Sample t-test
Experiment	0.245	0.080	0.000
Control		0.053	

The results of the assumption test are in Table 3. The significance value from the homogeneity test is 0.245. This indicates that the data variance in the two groups comes from homogeneous data. Table 3 also shows the significance values from the normality test. Both groups have a significance value of 0.080 and 0.053. These results exceed the significance level, indicating that both datasets are normally distributed. An independent sample t-test can be used as an inferential test in this study. The independent-samples t-test shows a p-value of 0.000 (< 0.05), indicating a statistically significant difference between the experimental and control groups. Therefore, the null hypothesis (H_0) is rejected, and the alternative hypothesis (H_1) is accepted.

The LIRACLE learning model has been shown to influence chemical literacy skills, as evidenced by an independent-samples t-test. This finding indicates that the LIRACLE learning model provides a more supportive learning environment for developing students' chemical literacy compared to conventional PBL. The integration of literacy-oriented activities, cooperative learning, and research-based inquiry enables students to connect chemical concepts to real-world contexts and engage in higher-order thinking.

In the first syntax in LIRACLE, the "problem initiation" syntax requires students to read a provided literacy text and then identify and formulate a problem contained within it (Pratama et al., 2025). This activity encourages students to connect scientific information in the text with real-world situations, which reflects important aspects of chemical literacy, including chemistry as context, chemistry as knowledge, and Higher Order Learning Skills (HOLS). From a theoretical perspective, this process aligns with Jerome Bruner's constructivist learning theory, which emphasizes that learning occurs when students actively construct knowledge by exploring information and identifying meaningful problems (Chand, 2026). Reading scientific texts and initiating problems can stimulate learners to organize prior knowledge and develop deeper conceptual understanding through inquiry-oriented thinking (Coffman et al., 2023).

In addition, this activity aligns with Lev Vygotsky's social constructivist perspective, which emphasizes the role of cognitive engagement and interaction in developing higher-level thinking. When students interpret literacy texts and formulate problems, they engage in analytical reasoning and contextual interpretation, processes that are fundamental to the development of scientific literacy and higher-order thinking skills (Lee & Chen, 2025).

The investigation stage encourages students to explore scientific information and evaluate evidence from multiple sources (Pimentel, 2025). This process supports the development of higher-order thinking skills and scientific reasoning, which are important components of chemical literacy. Among the LIRACLE syntaxes, the scientific paper writing stage plays a particularly important role in strengthening students' chemical literacy. In this stage, students collaboratively construct a coherent scientific article to communicate their findings and ideas. During the writing process, students are required to connect the chemistry concepts they have learned with problem-solving situations, explain the role of chemistry in addressing the problem, and describe the benefits of chemistry in real-life contexts. From a theoretical perspective, this activity aligns with the constructivist learning theory proposed by Lev Vygotsky, which emphasizes that knowledge is constructed through social interaction and collaborative dialogue (Kharroubi & ElMediouni, 2024; Alzate et al., 2025). Through group discussions and collaborative writing processes, learners exchange ideas, negotiate meaning, and refine their conceptual understanding of chemistry (Soysal & Türkmen, 2024). This collaborative interaction supports students in reaching their Zone of Proximal Development, where higher levels of understanding can be achieved with peer assistance (Ness, 2022; Lee & Chen, 2025). Consequently, the scientific writing activity facilitates the development of chemistry as knowledge, chemistry in context, and higher-order learning skills (HOLS).

The final syntax is communication, in which students present and discuss their research findings in a scientific discussion forum (Pratama et al., 2025). During the question-and-answer session, students respond to peers' and the lecturer's questions, requiring them to articulate their reasoning and justify their ideas with scientific evidence. From a theoretical perspective, this activity aligns with Lev Vygotsky's constructivist learning theory, which emphasizes that knowledge is constructed through social interaction and dialogue among learners. Through discussion and scientific argumentation, students refine their understanding and deepen their conceptual knowledge as they interact with peers within their Zone of Proximal Development (Lee & Chen, 2025).

Furthermore, this activity aligns with Jerome Bruner's learning theory, which emphasizes the importance of active learning and scaffolding in helping students construct knowledge through exploration and communication (Glazewski & Hmelo-Silver, 2019; Coffman et al., 2023). Scientific discussions and presentations provide opportunities for learners to organize, explain, and defend their ideas, which are important processes in the development of higher-order learning skills (HOLS), such as critical thinking, reasoning, and scientific argumentation.

Turning to the components of the LIRACLE model, the integration of Problem-Based

Learning (PBL) is theoretically and empirically grounded in its potential to foster chemical literacy. Previous studies have consistently demonstrated that PBL significantly contributes to students' chemical literacy, particularly in the domain of Higher Order Learning Skills (HOLS) (Zoller & Pushkin, 2007; Raman et al., 2024). Within the PBL framework, learning is initiated through authentic and contextual problems that require students to analyze situations, evaluate alternative explanations, and construct evidence-based solutions. These processes align with the principles of constructivism, which view learning as an active process in which learners construct knowledge through interaction with problems and experiences rather than passively receiving information (Al Abri et al., 2024).

From the perspective of Piaget's cognitive development theory, such activities facilitate processes of assimilation and accommodation, enabling students to reorganize and refine their cognitive structures when encountering new information or conflicting ideas (Sokoriyanto, 2016; Shukri & Toran, 2025). Through this active knowledge construction, students engage in higher-order cognitive processes that deepen conceptual understanding. Consequently, well-developed HOLS enable students to connect chemical concepts with real-world contexts, interpret chemical phenomena, and apply their knowledge to address problems (Arviani et al., 2023).

Cooperative learning has been linked with promoting students' chemical literacy when combined with an appropriate learning model (Habiddin et al., 2023). Previous research has examined the integration of cooperative learning with reading and writing skills, which can be applied in both social studies and science education (Habiddin et al., 2023; Edwards et al., 2023). In this study, cooperative learning complements Problem-Based Learning (PBL) as the primary learning model. Cooperative learning emphasizes structured group work in which each student has specific roles and responsibilities in solving learning tasks (Zhou et al., 2025).

From a theoretical perspective, cooperative learning is strongly supported by the work of Slavin, who proposed that effective cooperative learning occurs when group goals and individual accountability are combined (Yang, 2023; Zhou & Colomer, 2024). This structure encourages students to contribute, discuss ideas, and collaboratively construct understanding actively. Such interactions promote deeper conceptual understanding and reasoning processes, which are essential components of chemical literacy (Eymur & Geban, 2017).

In addition, cooperative learning aligns with Lev Vygotsky's social constructivist theory, which emphasizes that knowledge is constructed through social interaction. Through collaborative discussion and peer assistance within the Zone of Proximal Development, students can develop higher-level thinking skills beyond their individual capabilities (Lee & Chen, 2025). Therefore, integrating cooperative learning with literacy-oriented activities enhances the LIRACLE model's role in supporting students' chemical literacy development (Ardyansyah & Rahayu, 2024).

The improvement of students' chemical literacy through the LIRACLE learning model also has important implications for sustainable development. These findings support the objectives of the United Nations' Sustainable Development Goal 4, which emphasizes the development of critical thinking, scientific reasoning, and lifelong learning competencies (González-Pérez & Ramírez-Montoya, 2022). Chemical literacy enables students not only to understand chemical concepts but also to apply scientific knowledge to evaluate real-world issues related to environmental sustainability and resource use (Zidny et al., 2021).

Such competencies are also closely aligned with Sustainable Development Goal 12, which requires citizens to be able to make informed and responsible decisions about the use of chemical products and natural resources (Arora & Mishra, 2023). Through literacy-oriented problem analysis, collaborative inquiry, and research-based learning processes embedded in the LIRACLE model, students are encouraged to interpret scientific information and construct evidence-based solutions to problems critically (Pratama et al., 2025). Therefore, this study suggests that integrating literacy, research, collaboration, and problem-based learning into chemistry education can play a strategic role in preparing scientifically literate graduates capable of contributing to sustainable development and addressing complex global challenges.

CONCLUSION

The findings demonstrate that the LIRACLE learning model has a significant positive effect on undergraduate students' chemical literacy. Statistical analysis revealed a significant difference between students who learned using the LIRACLE model and those who learned using the PBL model, with the LIRACLE group achieving higher chemical literacy scores based on the chemical literacy rubric. These results indicate that integrating literacy-oriented activities, cooperative interaction, and research-based inquiry through the LIRACLE model can effectively support the development of chemical literacy in undergraduate chemistry learning. Therefore, LIRACLE offers a promising instructional approach to enhance students' chemical literacy in undergraduate education.

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