

Research Article

# Guiding Inquiry toward Sustainability: The Role of POGIL in Enhancing Grade 10 Students' Chemical Literacy in Green Chemistry

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## ABSTRACT

This study investigated the effect of the Process Oriented Guided Inquiry Learning (POGIL) model on Grade 10 students' chemical literacy in Green Chemistry topics using a quantitative experimental approach with an intact group comparison design. Two pre-existing classes were assigned as an experimental group taught using POGIL and a control group taught using Direct Instruction, with posttest-only assessment. The sample consisted of 59 Grade 10 students selected through purposive sampling (30 experimental, 29 control). A PISA-style chemical literacy test measuring content, context, and competency dimensions was used as the research instrument. Data were analyzed using descriptive statistics, tests of normality and homogeneity, and an independent samples t-test at a significance level of 0.05. The results showed that students taught using POGIL achieved a higher mean chemical literacy score (81.1) than those taught using Direct Instruction (70.1), with the difference being statistically significant ( $p < 0.05$ ). These findings demonstrate that the POGIL model has a positive effect on students' chemical literacy in Green Chemistry contexts and supports its application as a literacy- and sustainability-oriented instructional approach.

**Keywords:** Experimental Research; POGIL; Chemical Literacy; Green Chemistry

## 1. INTRODUCTION

Chemistry learning in the twenty-first century can no longer be oriented solely toward mastery of concepts; it must also foster students' scientific literacy and chemical literacy so that they are prepared to address complex real-world problems and the challenges of sustainable development (Busquets et al., 2021; Haetami et al., 2023; Tiara & Sulistina, 2021). Rapid advances in science and technology, including the demands of the Industrial Revolution 4.0, require individuals to possess higher-order thinking skills, problem-solving abilities, collaboration skills, and the capacity to make evidence-based decisions in scientific contexts (Arsyad et al., 2024; Eichler & Peebles, 2016). Within the science curriculum, scientific literacy has long been positioned as a primary goal of educational reform, as it plays a crucial role in shaping citizens who are able to participate critically in socio-scientific issues (Haetami et al., 2023; She et al., 2019).

Results from the international assessment Programme for International Student Assessment (PISA) indicate that students' scientific literacy achievement in many countries, including Indonesia, remains relatively low (She et al., 2019; Tiara & Sulistina, 2021). PISA instruments are designed to assess students' abilities to explain phenomena scientifically, design and evaluate investigations, and interpret data and scientific evidence in everyday contexts (Distler et al., 2022; She et al., 2019). Numerous studies have revealed that scientific literacy and chemical literacy are closely related to epistemic beliefs about science, learning motivation, interest in science, and learning experiences that emphasize inquiry-based approaches (Muliaman, 2021; She et al., 2019). Other research has also confirmed that contextual tasks based on the PISA model are able to promote higher-order cognitive achievement and enhance students' scientific literacy in chemistry learning (Distler et al., 2022). The low level of scientific and chemical literacy among Indonesian students has often been associated with school-related and socio-economic factors, as well as, most importantly, with instructional practices that have not optimally developed the dimensions of context, content, scientific processes, and scientific attitudes (Haetami et al., 2023; Muliaman et al., 2022; Tiara & Sulistina, 2021).

Chemical literacy is understood as an individual's ability to use chemical knowledge to understand phenomena, make decisions, and take positions on issues involving chemical substances and processes in society. A number of studies indicate that chemical literacy encompasses competencies such as explaining scientific phenomena, designing and evaluating investigations, and assessing scientific information across various chemistry topics that are closely related to everyday life

(Muliaman & Ginting, 2022; Salsabila & Hernani, 2025). Literature reviews have also reported the development of chemistry modules and literacy instruments based on the PISA framework and the chemical literacy model proposed by Shwartz et al., which have been shown to be valid, reliable, and to have a positive impact on students' chemical literacy (Suwahyu & Rahayu, 2023; Tiara & Sulistina, 2021). In addition, learning that integrates socio-scientific issues, technology, and real-life contexts has been considered effective in developing the declarative, procedural, and epistemic dimensions of chemical literacy (Haetami et al., 2023; Muliaman et al., 2018; Sari et al., 2025).

Various global environmental problems, such as pollution, hazardous waste, energy crises, and climate change, demand a generation with strong chemical literacy and the ability to make decisions oriented toward sustainability (Kouloughliotis et al., 2024; Widya, Mujtahid, Muliaman, et al., 2024). Green Chemistry offers twelve principles that emphasize pollution prevention, waste minimization, the use of renewable feedstocks, and the design of chemical processes that are safe for humans and the environment. The integration of green chemistry concepts in secondary education has been reported to enhance students' knowledge, interest, and positive attitudes toward sustainable chemical practices, while also linking chemistry concepts to real environmental issues such as waste management, alternative energy sources, and recycling. International reviews indicate that the implementation of green chemistry in secondary schools generally employs inquiry-based, contextual, problem-based learning and socio-scientific issue approaches, which are effective in developing students' cognitive and affective domains. Therefore, strengthening chemical literacy through green chemistry contexts is a strategic step in preparing learners who possess environmental awareness and functional scientific literacy (Salsabila & Hernani, 2025; Widya, Mujtahid, Hidayat, et al., 2024).

Nevertheless, chemistry instruction in many countries, including Indonesia, is still dominated by teacher-centered approaches through lecturing and direct instruction (Cavinato, 2017; Wang et al., 2024). Numerous national and international studies have reported that although the effectiveness of active learning for learning outcomes and student engagement has been well established, the adoption of active learning strategies—such as POGIL, problem-based learning, and flipped classrooms—remains relatively limited, with most educators continuing to rely on traditional instruction (Eichler & Peeples, 2016; Nardo et al., 2022). Laboratory activities that follow “cookbook” procedures have also been reported to be less effective in developing problem-solving skills, critical thinking, experimental design abilities, and the application of knowledge in real-world contexts (Kovarik et al., 2022). At the secondary education level, the dominance of conventional instructional approaches has often been associated with low learning motivation, conceptual difficulties, and limited opportunities for students to construct knowledge independently, engage in argumentation, and develop scientific literacy (Zemene et al., 2025).

In response to these conditions, the literature widely recommends a shift toward active, student-centered learning through inquiry-based approaches, problem-based learning, and the integration of socio-scientific issues to enhance scientific and chemical literacy (Arsyad et al., 2024; Irwanto et al., 2024). Inquiry-based learning is regarded as one of the most effective approaches for developing scientific abilities, conceptual understanding, and the contextualization of knowledge in science learning. In chemistry education, various innovations such as multi-representation-based modules, STEM-based learning, green chemistry, contextual learning, cooperative learning, and inquiry-based approaches have been reported to train competencies aligned with the PISA framework, namely explaining phenomena, designing investigations, and evaluating scientific evidence. Approaches based on socio-scientific issues in topics relevant to students' lives have also been shown to optimize chemical literacy while simultaneously fostering positive attitudes and values toward science and the environment (Haetami et al., 2023; Nabila et al., 2024).

One active inquiry-based instructional model that has been widely investigated for its effectiveness is Process Oriented Guided Inquiry Learning (POGIL). This model engages students in small groups with structured roles to explore models, respond to scaffolded questions, and construct concepts through stages of exploration, concept invention, and application, while simultaneously developing science process skills and twenty-first-century skills such as communication, collaboration, and critical thinking. Numerous studies have demonstrated that the implementation of POGIL can enhance conceptual understanding, academic achievement, and positive attitudes toward chemistry learning compared to traditional lecture-based methods. In several chemistry topics, such as electrochemistry, POGIL has been reported to yield higher posttest scores with significant effect sizes and to receive positive responses from students (Puspitasari et al., 2024; Zemene et al., 2025). Other studies have shown that the application of POGIL in salt hydrolysis topics positively influences senior high school students' chemical literacy. Moreover, the combination of POGIL with the Science-Technology-Society-Environment (SETS) approach in buffer solution contexts has been reported to significantly improve both chemical literacy and science process skills, with the experimental group achieving higher levels of chemical literacy than the control group (Puspitasari et al., 2024). Although empirical evidence regarding the effectiveness of POGIL on learning outcomes, process skills, and chemical literacy is substantial, its implementation at the secondary school level, particularly within the context of green chemistry, remains relatively limited (Kouloughliotis et al., 2024; Puspitasari et al., 2024; Wang et al., 2024). Reviews of green chemistry implementation in secondary education indicate that despite strong global interest in this topic, classroom practices have not fully utilized structured inquiry models such as POGIL to link green chemistry principles with the enhancement of students' chemical literacy. In Indonesia, literature reviews reveal considerable potential for integrating the PISA framework, environmental issues, and active learning models to address low levels of chemical literacy. However, experimental studies that specifically examine the effect of the POGIL model on

chemical literacy in green chemistry topics at the senior high school level are still very scarce. This condition highlights a research gap as well as an urgent need to empirically investigate the application of POGIL in green chemistry instruction as an effort to strengthen students' chemical literacy and to prepare a generation that is environmentally conscious and equipped with a sustainability-oriented perspective (Celestino, 2023; Puspitasari et al., 2024).

Chemical literacy is an integral component of scientific literacy that emphasizes individuals' ability to apply concepts, procedures, and scientific ways of thinking in contexts involving chemical substances and chemical phenomena in everyday life. Individuals who possess chemical literacy do not merely understand facts and formulas; rather, they are able to explain chemical phenomena, interpret data, and evaluate chemistry-based information in order to make responsible decisions for themselves and their surrounding environment (Andriani et al., 2018; Husna et al., 2025; Wibowo & Ariyatun, 2020). Referring to the PISA framework, scientific literacy which can be adapted as a framework for chemical literacy comprises three main dimensions: content, context, and competencies. The content dimension relates to mastery of chemical concepts, such as chemical reactions, structure of matter, and acids–bases, as well as procedural and epistemic knowledge concerning how such knowledge is generated and scientifically justified. The context dimension emphasizes the application of chemical concepts in various life situations at the personal, local, national, and global levels, including health, natural resource utilization, environmental quality, and chemical risks (Andriani et al., 2018; Khery et al., 2022; Milanto et al., 2021). Meanwhile, the competency dimension includes the ability to explain phenomena scientifically, design or evaluate scientific investigations, and interpret data and scientific evidence in chemistry-related contexts. Various instruments and instructional designs developed based on the PISA framework have been shown to train these three dimensions and thereby improve students' scientific literacy profiles (Husna et al., 2025; Setyaningsih et al., 2019).

In the context of scientific decision-making in society, chemical literacy plays a crucial role because many public issues such as food safety, pharmaceuticals, cosmetics, air and water pollution, and the use of household chemicals—require a basic understanding of the properties and risks of chemical substances. Individuals with strong scientific literacy are generally better able to weigh evidence, evaluate scientific claims, and participate reflectively in public discussions concerning science and technology. Several studies indicate that low scientific literacy leads students to experience difficulties in connecting scientific concepts with real-world contexts, which may hinder their ability to make appropriate decisions regarding scientific issues (Milanto et al., 2021; Wibowo & Ariyatun, 2020). Within the context of Green Chemistry, chemical literacy serves as a fundamental basis for understanding and applying principles of pollution prevention, waste minimization, selection of renewable feedstocks, and the design of chemical processes that are safe for humans and the environment. Chemistry instruction that integrates ethnoscience, environmental issues, and sustainable practices has been shown to enhance students' scientific and chemical literacy, while simultaneously fostering more environmentally responsible attitudes. Therefore, developing chemical literacy through Green Chemistry contexts not only contributes to conceptual understanding but also supports the formation of ecological awareness and responsibility among students (Erna et al., 2021; Wibowo & Ariyatun, 2020).

The Process Oriented Guided Inquiry Learning (POGIL) model is grounded in constructivist theory and inquiry-based approaches, which view knowledge as actively constructed by learners through social interaction and exploration of meaningful problems (Fajri et al., 2023; Patonah, 2020). From a constructivist perspective, teachers act as facilitators who design learning experiences that enable students to construct concepts independently through cycles of exploration, concept invention, and application. POGIL employs guided inquiry, in which students manipulate data or models, respond to sequenced questions, and derive scientific principles with the support of guiding prompts rather than through direct instruction (Malik et al., 2017; Rodriguez et al., 2020). Operationally, POGIL is implemented through self-managed small-group work with structured roles, such as manager, recorder/presenter, reader, and reflector, to ensure active participation and the development of process skills. The instructional phases of POGIL generally include orientation, exploration of models or data, concept invention, application of concepts to new situations, and closure or reflection. Learning activities are designed in a scaffolded manner, enabling students to progress from the analysis of concrete data toward conceptual generalization and subsequently apply these concepts to more complex problems (Fajri et al., 2023; Husna et al., 2025; Rodriguez et al., 2020).

Numerous studies have reported that POGIL is effective in developing science process skills, including observation, variable identification, hypothesis formulation, experimental design and interpretation, as well as scientific argumentation skills. The application of POGIL in chemistry and other science subjects has also been shown to enhance conceptual understanding, reduce misconceptions, and strengthen students' critical and analytical thinking abilities. Quasi-experimental studies on topics such as hydrocarbons, static fluids, and solubility equilibrium have demonstrated significant improvements in science process skills and learning outcomes, with moderate to high N-gain categories in classes implementing POGIL compared to control classes (Erna et al., 2021; Fajri et al., 2023; Patonah, 2020). With regard to literacy development, POGIL has strong potential to enhance scientific and chemical literacy because its learning activities require students to explain scientific phenomena, use evidence, interpret data, and connect concepts with real-world contexts—competencies that align closely with the PISA framework. POGIL integrated with socio-scientific issue contexts has been reported to significantly improve argumentation skills compared to POGIL without contextual integration or conventional instruction. Furthermore, the combination of POGIL with context-based worksheets or with other instructional models, such as Discovery Learning and MFI, has been shown to enhance students' critical thinking,

creativity, and scientific literacy (Setyaningsih et al., 2019; Talakua & Sahureka, 2020). Thus, POGIL represents a highly promising instructional model for developing science process skills and twenty-first-century chemical literacy.

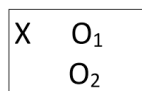
Research on the implementation of POGIL in chemistry and science education has expanded across various educational levels. Literature reviews indicate that the consistent use of POGIL is effective in improving students' learning outcomes and conceptual understanding at both secondary and higher education levels. Experimental studies in senior high school chemistry classes have reported that POGIL effectively reduces misconceptions in solubility equilibrium topics, with a reduction of approximately 47% achieved through structured inquiry activities. Other studies have also demonstrated significant improvements in science process skills and procedural knowledge when POGIL is compared with conventional inquiry instruction or lecture-based methods, as evidenced by high N-gain values and statistically significant differences between experimental and control groups (Erna et al., 2021; Yusuf, 2019). Beyond its impact on cognitive outcomes, POGIL also contributes to the development of higher-order thinking skills. The application of POGIL in physics and biology instruction has been reported to improve critical and analytical thinking skills at moderate to high levels, along with very high levels of student learning activity. Research in geography education likewise indicates that POGIL is significantly more effective in enhancing critical thinking skills than traditional instruction, highlighting the model's cross-disciplinary applicability (Malik et al., 2017; Pinasthi et al., 2024; Talakua & Sahureka, 2020). International research reviews conclude that, overall, POGIL yields better learning outcomes than traditional lectures, although many studies continue to emphasize broad quantitative measures and have yet to explore underlying theoretical mechanisms in depth (Rodriguez et al., 2020).

On the other hand, studies on context-based scientific and chemical literacy emphasize the importance of employing the PISA framework (content, context, and competencies) in the design of assessment instruments and instructional practices. Analyses of scientific literacy among junior and senior high school students in various regions reveal that average achievement remains in the low to moderate category, with dominance of lower PISA competency levels and weak procedural and epistemic knowledge. Chemistry instruction based on ethnoscience and local contexts has been reported to enhance students' scientific literacy with higher N-gain values compared to control classes, and is therefore recommended as an approach for developing chemical literacy. Other studies indicate that inquiry-based, problem-solving, and context-based learning approaches are effective in strengthening PISA-related competencies, particularly in explaining phenomena and interpreting data (Andriani et al., 2018; Khery et al., 2022; Milanto et al., 2021). Nevertheless, several important research gaps remain. First, many POGIL studies focus on general learning outcomes, critical thinking skills, or science process skills, while relatively few explicitly measure chemical literacy using the PISA framework (content–context–competencies) (Fajri et al., 2023; Patonah, 2020). Second, although context-based scientific and chemical literacy research has employed ethnoscience, inquiry, and local context approaches, systematic integration between the POGIL model and the specific context of Green Chemistry has rarely been reported, particularly at the senior high school level (Rodriguez et al., 2020; Wibowo & Ariyatun, 2020). Third, most existing studies concentrate on specific chemistry topics, such as acids–bases, equilibrium, and hydrocarbons, leaving the impact of POGIL on chemical literacy in environmentally rich topics such as Green Chemistry underexplored (Setyaningsih et al., 2019). These conditions open opportunities for research to examine the effects of a Green Chemistry context-based POGIL model on senior high school students' chemical literacy using an assessment framework aligned with PISA.

The research question of this study is whether there is an effect of the POGIL model on students' chemical literacy in green chemistry topics. The objective of this study is to determine the effect of the POGIL model on students' chemical literacy in green chemistry topics. The research hypotheses are formulated as follows: **H<sub>a</sub>**: there is a significant effect of the POGIL model on students' chemical literacy in green chemistry topics; **H<sub>0</sub>**: there is no significant effect of the POGIL model on students' chemical literacy in green chemistry topics

## 2. RESEARCH METHOD

This study employed a quantitative approach using an experimental method. The research design applied was the *intact group comparison design* (Sugiyono, 2013), in which two pre-existing classes were given different instructional treatments and subsequently assessed using a posttest only. This design is commonly used in school-based research when individual randomization is difficult to implement, yet it still allows for causal analysis through appropriate statistical control.



**Figure 1.** Intact Group Comparison Design

Notation:

O<sub>1</sub> = Posttest scores of chemical literacy for students taught using the POGIL model

O<sub>2</sub> = Posttest scores of chemical literacy for students taught using Direct Instruction

The population of this study comprised all Grade 10 students who learned Green Chemistry at the selected school. The sample consisted of two Grade 10 classes selected through *purposive sampling* (Sugiyono, 2013), in which classes were

chosen based on specific criteria relevant to the research objectives, such as equivalence of prior ability, similar schedules, or the same instructor. The research subjects included 30 students in the experimental class and 29 students in the control class. The independent variable in this study was the POGIL instructional model, while the dependent variable was students' chemical literacy in Green Chemistry topics. The experimental class received instruction using the Process Oriented Guided Inquiry Learning (POGIL) model, whereas the control class was taught using Direct Instruction in the form of structured lectures. Both classes were taught the same subject matter, namely Green Chemistry.

The research instrument was a PISA-style chemical literacy test designed to assess the dimensions of content, context, and competencies. The instrument was developed or adapted from PISA-based chemical literacy frameworks and was subjected to content and empirical validity testing through expert judgment, item difficulty analysis, item discrimination, item-total correlation, as well as reliability testing (Arikunto, 2021). Data were collected through the administration of a chemical literacy posttest to both the experimental and control classes. Data analysis included descriptive statistics such as mean scores, standard deviations, and score categories. Prior to hypothesis testing, the data were examined using tests of normality and homogeneity of variance as prerequisites for parametric analysis. To determine differences in chemical literacy between students taught using the POGIL model and those taught using Direct Instruction, an independent samples t-test was conducted at a significance level of  $\alpha = 0.05$

### 3. RESULTS AND DISCUSSION

#### 3.1 Results

##### Descriptive Statistics of Students' Chemical Literacy

Chemical literacy data were obtained from a posttest administered to the experimental class (POGIL) and the control class (Direct Instruction). The descriptive statistics of the posttest results are presented in Table 1.

Table 1. Descriptive Statistics

	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Chemistry Literacy Score for the Experiment Class	30	74,00	88,00	2434,00	81,1333	3,96305
Chemistry literacy scores for the control class	29	62,00	76,00	2033,00	70,1034	3,46765
Valid N (listwise)	29					

Based on Table 1, the mean chemical literacy score of students taught using the POGIL model was higher than that of students taught using Direct Instruction. The difference in mean scores between the two classes was **11 points**, indicating a substantial difference in chemical literacy achievement. In addition, the score range of the experimental class fell within the moderate to high category, whereas the scores of the control class tended to be in the low to moderate category. Descriptively, these results indicate that instruction using the POGIL model contributed positively to students' chemical literacy achievement in Green Chemistry topics.

##### Assumption Testing

Prior to hypothesis testing using parametric analysis, the posttest data were examined through tests of normality and homogeneity of variance.

##### Normality Test

The results of the normality test indicated that the chemical literacy scores of both the experimental and control classes were normally distributed, as the significance values (p) for each class were greater than 0.05 ( $p > 0.05$ ). Thus, the assumption of normality was satisfied.

Table 2. Tests of Normality

Learning Model		Kolmogorov-Smirnov <sup>a</sup>			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Chemistry Literacy	Model POGIL	0,079	30	.200*	0,972	30	0,599
	Model DI	0,119	29	.200*	0,975	29	0,690

\*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Based on the normality test, it was found that the data is **normally** distributed because the sign value is  $> 0.05$ .

##### Homogeneity of Variance Test

The homogeneity of variance test showed that the variances of chemical literacy scores between the experimental and

control classes were homogeneous, as indicated by the Levene's test significance value being greater than 0.05 ( $p > 0.05$ ). Therefore, the data met the requirements for analysis using an independent samples t-test.

**Table 3.** Test of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
Chemistry	Based on Mean	0,812	1	57	0,371
Literacy	Based on Median	0,788	1	57	0,378
Posttest Score	Based on Median and with adjusted df	0,788	1	56,949	0,378
	Based on trimmed mean	0,820	1	57	0,369

Based on the homogeneity test, it was found that the posttest data of both classes was **homogeneous** because the sign value was  $> 0.05$ .

### Hypothesis Testing

Hypothesis testing was conducted using an independent samples t-test to determine differences in chemical literacy between students taught using the POGIL model and those taught using Direct Instruction. The results of the t-test are presented in **Table 4**.

**Table 4.** Independent Samples Test

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
							Lower	Upper
Chemistry	Equal variances assumed	11,362	57	0,000	11,02989	0,97081	9,08587	12,97390
Literacy	Equal variances not assumed	11,388	56,452	0,000	11,02989	0,96859	9,08991	12,96986
Posttest Scores								

The results of the independent samples t-test indicated that the significance value (Sig. 2-tailed) was less than 0.05 ( $p < 0.05$ ). Accordingly, the null hypothesis ( $H_0$ ) was rejected and the alternative hypothesis ( $H_a$ ) was accepted. there is a significant effect of the POGIL model on students' chemical literacy in green chemistry topics.

### 3.2. Discussion

The mean chemical literacy score of students in the POGIL class (81.1) was substantially higher than that of students in the Direct Instruction class ( $\pm 70.1$ ). This finding is consistent with numerous studies reporting that POGIL enhances academic achievement, conceptual understanding, and scientific or chemical literacy more effectively than traditional instruction (Barthlow & Watson, 2014; Hein, 2012; Ripa Jummaro et al., 2024). Such advantages can be attributed to the constructivist foundation of POGIL, in which students actively learn through small-group work to explore models or data, construct concepts, and apply them to new situations (Moog & Spencer, 2008; Moon et al., 2017). Pedagogically, the POGIL learning cycle comprising exploration, concept invention, and application provides students with opportunities to interpret information, connect multiple chemical representations, and engage in systematic problem solving. These activities reflect the core components of PISA-style chemical literacy, which emphasize explaining phenomena, interpreting data, and applying chemical knowledge in real-world contexts (Ardhana, 2020; Irwanto et al., 2024). Accordingly, the structure of POGIL inherently aligns with the demands of twenty-first-century chemical literacy development.

Furthermore, the structured group work in POGIL, including clearly defined roles such as manager and recorder and team accountability, promotes scientific communication, self-regulation, and evidence-based argument evaluation (68). Previous research has demonstrated that POGIL effectively reduces misconceptions, particularly in abstract chemical concepts such as particulate nature of matter and electrochemistry (Barthlow & Watson, 2014; Zemene et al., 2025). It has also been shown to improve critical thinking and problem-solving skills (Aiman et al., 2020), as well as foster positive attitudes and self-efficacy toward chemistry learning (Qureshi et al., 2017). The combination of higher-order cognitive engagement, collaborative learning, and the teacher's role as a *guide on the side* provides a strong explanation for why students in the POGIL class achieved higher levels of chemical literacy than those in lecture-based instruction (Moog & Spencer, 2008; Özkanbaş & Taştan Kırık, 2020). The Green Chemistry context further strengthens the effectiveness of POGIL, as it introduces authentic issues closely related to students' everyday lives, such as waste management, pollution,

hazardous substances, and sustainability. These issues are particularly well suited to inquiry-based approaches like POGIL (Aiman et al., 2020; Puspitasari et al., 2024). The literature indicates that when science learning is embedded in socially and environmentally relevant contexts, scientific and chemical literacy as well as environmental awareness tend to improve, because students are required to apply scientific concepts to evaluate impacts and make responsible decisions (Rumain & Geliebter, 2020).

In Green Chemistry-based POGIL instruction, students analyze environmental cases, interpret experimental data, or examine industrial scenarios, and subsequently formulate principles and environmentally friendly solutions. Such activities align with scientific literacy frameworks that emphasize explaining phenomena, interpreting data, and evaluating technological options within societal and environmental contexts. Supporting this perspective, studies combining POGIL with the Science-Technology-Society-Environment (SETS) approach have reported significant improvements in chemical literacy and science process skills, reinforcing the use of Green Chemistry contexts as an effective medium for chemical literacy development (Puspitasari et al., 2024; Rumain & Geliebter, 2020). Overall, the findings of this study are consistent with reviews and empirical research concluding that POGIL enhances learning outcomes, conceptual understanding, literacy, and science process skills across various educational levels and chemistry contexts. Studies involving senior high school students and university students have reported higher exam scores, ACS percentiles, and N-gain values in POGIL classes compared to lecture-based classes (Cascolan, 2023; Hein, 2012). Research specifically addressing chemical literacy has also documented significant gains when POGIL or POGIL combined with the SETS approach is implemented (Irwanto et al., 2024; Puspitasari et al., 2024). Nevertheless, the magnitude of POGIL's effects varies across studies. Some research reports very large effects in abstract topics such as electrochemistry, particulate matter, and stoichiometry (Cascolan, 2023; Zemene et al., 2025), whereas other studies find more pronounced improvements in process skills, attitudes, and students' confidence. These variations may be explained by differences in the quality of POGIL materials, the extent of teacher training, the duration of the intervention, and students' readiness for collaborative inquiry-based learning. Cultural context also plays a role; studies conducted in high-context environments such as Qatar and Saudi Arabia indicate that while POGIL remains effective, it requires adaptation and stronger facilitation strategies (Alghamdi & Alanazi, 2020; Qureshi et al., 2017). In the present study, the highly relevant Green Chemistry context likely amplified the impact of POGIL on chemical literacy, as also reported in other context-rich topics (Ardhana, 2020). From a theoretical perspective, these findings support social constructivist frameworks and cognitive models of chemistry learning that emphasize the role of meaningful activities, multiple representations, and social interaction in concept construction (Ardhana, 2020; Moog & Spencer, 2008). POGIL demonstrates that when instructional tasks require data analysis, scientific argumentation, and application of concepts in authentic contexts, not only declarative knowledge but also chemical literacy and scientific process skills can be developed (Pond & Williams, 2020; Vishnumolakala et al., 2017). Consequently, this study reinforces a literacy- and sustainability-oriented paradigm of chemistry education, rather than one focused solely on rote memorization of facts.

## 4. CONCLUSION

Based on the results of the statistical analysis of students' posttest scores on chemical literacy in Green Chemistry topics, it can be concluded that students who were taught using the POGIL (Process Oriented Guided Inquiry Learning) model achieved a higher mean chemical literacy score than those who learned through Direct Instruction. Furthermore, the findings indicate that the implementation of the POGIL model had a positive effect on enhancing students' chemical literacy in the context of Green Chemistry when compared to Direct Instruction.

## RECOMMENDATIONS

Based on the findings of this research, several recommendations can be proposed as follows : 1. The implementation of POGIL can be combined with authentic assessment strategies, such as project-based tasks or case studies, in order to obtain a more comprehensive picture of students' chemical literacy. 2. Future studies may be conducted at different educational levels and across various chemistry topics to examine the consistency of POGIL's effectiveness in developing chemical literacy. 3. It is also recommended to include additional variables, such as critical thinking skills, environmental attitudes, or learning motivation, to capture the broader impact of the POGIL model. 4. Further research should employ stronger experimental designs, for example a pretest-posttest control group design, to provide a more detailed analysis of gains in chemical literacy. 5. In addition, qualitative or mixed-methods studies are needed to explore more deeply the interaction processes, thinking patterns, and challenges experienced by students during POGIL-based instruction in the context of Green Chemistry

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