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Effectiveness of a Green Analytical Chemistry-Based Problem-Based Learning Model in Improving Environmental Literacy among Pharmacy Students

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Abstract
This study aims to analyse the effectiveness of the Green Analytical Chemistry (GAC)-based Problem-Based Learning (PBL) model in improving pharmacy students' environmental literacy. This study used a quasi-experimental design with a Nonequivalent Control Group Pretest–Posttest Design. The study sample consisted of 60 Pharmacy Study Program students divided into an experimental group and a control group. The experimental group received GAC-based PBL, while the control group received direct instruction. The treatment was carried out over five meetings on the following topics: basic analytical chemistry techniques, physical and chemical properties of drug molecules, acids and bases, instrumental analysis, and reduction–oxidation reactions. The research instrument was an environmental literacy test that measured environmental knowledge, attitudes, environmental problem-solving competencies, and environmental behaviour. Data were analysed using the N-Gain test, Independent Samples t-test, and Cohen's d. The results showed that the experimental group achieved a greater increase in environmental literacy than the control group, with N-Gain values of 0.7040 and 0.3963, respectively. The results of the Independent Samples t-test showed a significant difference between the two groups ($p < 0.05$). The findings of this study indicate that the PBL model based on Green Analytical Chemistry was effective in improving the environmental literacy of pharmacy students.

Keywords: Analytical Chemistry; Environmental Literacy; Green Analytical Chemistry; Problem-Based Learning

INTRODUCTION

The Industrial Revolution 4.0 and the transformation toward a green economy have driven a paradigm shift in higher education, particularly in the health and science sectors. The development of the pharmaceutical industry and health laboratories requires pharmacy graduates not only to possess scientific and technical competencies but also to apply sustainability principles in their professional practice. In this context, analytical chemistry laboratory activities are a significant concern because they still rely on hazardous chemicals, generate waste, and consume significant energy if not managed in accordance with sustainability principles. The concept of Green Analytical Chemistry (GAC) was developed to minimise the use of hazardous reagents, reduce waste generation, increase energy efficiency, and encourage the implementation of more environmentally friendly analytical methods (Sajid & Płotka-Wasylka, 2022). Furthermore, analytical laboratories reportedly consume five to ten times more energy than office spaces of comparable size and can contribute approximately 60% of energy consumption and carbon emissions in university environments. This situation emphasises the importance of integrating sustainability principles into laboratory learning to develop environmental competency in prospective healthcare workers and scientists (Freese et al., 2024;

Miladinović, 2024).

Analytical chemistry instruction in the Pharmacy Study Program is still dominated by the pursuit of accurate analytical results and the mastery of laboratory procedures, while environmental sustainability has not been optimally integrated into the learning process. Students are primarily directed toward obtaining accurate analytical results, but they are not systematically trained to consider safer chemical use, waste reduction, reagent efficiency, or the environmental impact of selected analytical methods. This situation highlights the need for a learning model that integrates analytical competency with environmental awareness, enabling pharmacy students to make decisions that consider both scientific and sustainable aspects.

Green Analytical Chemistry (GAC) is emerging as a modern analytical paradigm that emphasises reducing the use of hazardous chemicals, minimising waste, energy efficiency, and utilising more sustainable analytical methods without compromising the quality of analytical results. Recent developments indicate that GAC is no longer viewed solely as a technical approach to chemical analysis, but also as a strategy to support the achievement of sustainable development goals through the application of environmentally responsible analytical methods (Meher & Zarouri, 2025). In addition to encouraging the development of more environmentally friendly analytical methods, GAC provides various metrics for evaluating the sustainability of an analytical method, allowing environmental aspects to be considered alongside analytical performance. In the context of higher education, the integration of GAC principles into laboratory learning has been shown to improve students' understanding of sustainable laboratory practices, strengthen their ability to evaluate the environmental impact of analytical methods, and foster professional awareness of chemical waste management and efficient resource use (Streuli et al., 2025). Furthermore, green chemistry-based education has been reported to improve student learning outcomes, critical thinking skills, and environmental awareness, enabling graduates not only to possess scientific competence but also to apply sustainability principles in their professional practice (Sunday et al., 2026).

Problem-Based Learning (PBL) is a learning model that places students at the centre of the learning process through authentic, contextual, and unstructured problem-solving (Barrows, 1996). The characteristics of PBL, which encourage students to identify, analyse, and solve real-world problems, make it suitable for developing higher-order thinking skills, critical thinking, and decision-making in the context of sustainability-based learning (Loyens et al., 2025; Yu & Zin, 2023). Recent studies have shown that the use of PBL in chemistry and health education can increase student engagement, strengthen conceptual understanding, and connect scientific concepts to real-world problems, thereby preparing students to face complex professional challenges. In this study, PBL is integrated with the principles of Green Analytical Chemistry throughout each learning session. Students begin by identifying problems related to chemical use, laboratory waste, and their impact on the environment. Next, students organise information and conduct investigations to design analytical procedures that not only meet analytical accuracy but also implement GAC principles, such as safer reagent use, waste reduction, and efficient chemical use. The results of the investigations are then presented and evaluated based on their scientific rigour and environmental impact. Through this integration, students not only develop critical thinking and problem-solving skills but also learn to connect analytical chemistry concepts with sustainable laboratory practices, enabling them to make decisions that consider both scientific aspects and environmental responsibility. These findings are supported by a systematic review of green chemistry education, which concluded that learning that integrates sustainability contexts and authentic problem-solving consistently improves students' sustainability competencies, critical thinking skills, and environmental awareness.

Environmental literacy is defined as an individual's ability to understand environmental systems, evaluate the impacts of human activities on the environment, and make responsible decisions informed by knowledge, skills, attitudes, and a commitment to sustainability (Roth, 1992; Hollweg et al., 2011). Recent studies have shown that environmental literacy is a multidimensional construct encompassing cognitive, affective, behavioural, and action competency dimensions, enabling individuals to actively participate in resolving environmental problems (Ardoin et al., 2020). Previous research has also shown that problem-based and contextual learning approaches can improve critical thinking, environmental awareness, and decision-making in students across various disciplines, including science and health (Loyens et al., 2025; Varadarajan & Ladage, 2024). In the context of pharmacy education, there is a growing need to prepare graduates who possess not only technical competence in chemical analysis but also sustainability and environmental responsibility, given the critical role of pharmacy professionals in supporting sustainable drug use, pharmaceutical waste management, and protecting public health. Furthermore, numerous studies on sustainability education in higher education have shown that integrating environmental issues into core courses has a greater impact on the development of sustainability competencies than when they are taught as separate subjects outside students' disciplinary contexts (Brundiers et al., 2021).

Although research on Problem-Based Learning, Green Analytical Chemistry (GAC), and environmental literacy has flourished in recent years, these three areas are still generally studied separately. Most PBL research focuses on improving critical thinking skills, problem-solving skills, or student learning outcomes (Loyens et al., 2025;Varadarajan & Ladage, 2024), while GAC research focuses more on developing environmentally friendly analytical methods, evaluating the sustainability of analytical methods, and implementing green chemistry principles in the laboratory (Mehta et al., 2024; Yin et al., 2024). Furthermore, research on environmental literacy in pharmacy education generally focuses on increasing environmental knowledge or awareness, while studies integrating active learning strategies with comprehensive sustainability competency development are limited (Miladinović, 2025).

How learning designs that combine active pedagogical approaches with Green Analytical Chemistry principles can effectively shape the environmental literacy of prospective pharmacists. The development and testing of a Green Analytical Chemistry-based Problem-Based Learning model that not only uses contextual problems as learning triggers but also utilises the twelve principles of Green Analytical Chemistry (GAC) as a framework for problem identification, analysis of alternative solutions, selection of analytical methods, and evaluation of the environmental impact of each laboratory decision in analytical chemistry courses. Unlike previous studies that implemented PBL or GAC separately, this study integrates both into a single learning design to improve pharmacy students' environmental literacy, encompassing knowledge, attitudes, critical thinking skills, and environmentally responsible decision-making. This integration is expected to produce a learning model that is more relevant to the demands of sustainable pharmacy education and the needs of the healthcare industry in the green-economy era.

This study aims to analyse the effectiveness of the Green Analytical Chemistry-based Problem-Based Learning model in improving pharmacy students' environmental literacy. This research is expected to make theoretical contributions by strengthening the relationships among constructivist pedagogy, green chemistry education, and environmental literacy, while also providing practical contributions to the development of a sustainability-oriented pharmacy curriculum.

METHODS

Research Design

This study used a quasi-experimental method with a Nonequivalent Control Group Pretest–Posttest Design. This design was chosen because the study was conducted in intact classes, so the researcher could not randomly assign participants to the experimental or control groups (Creswell & Cresswel, 2018). Both classes were from the same study program, semester, and subject, thus having relatively comparable characteristics. Before the treatment was administered, all participants in both groups took a pretest (O_1) to measure their initial environmental literacy skills. Next, the experimental group received instruction using the

Problem-Based Learning model based on Green Analytical Chemistry (PBL-GAC), while the control group received direct instruction that has been applied in Analytical Chemistry courses. In the control group, learning was conducted using a teacher-centred approach, in which the lecturer conveyed analytical concepts and procedures through lectures, explanations of materials, and practical demonstrations. Students followed the lecturer's explanations, completed exercises, and carried out practicums according to the module's instructions without using problem-solving scenarios or integrating Green Analytical Chemistry principles, such as reducing the use of hazardous reagents, minimising waste, and selecting more environmentally friendly analytical methods. After the entire learning series was completed, both groups were given a posttest (O_2) to measure changes in environmental literacy after the treatment. This design allows comparison of changes in pretest and posttest scores between the experimental and control groups, enabling more objective evaluation of the effectiveness of the PBL-GAC model. In addition, using the same pretest and posttest in both groups helps reduce threats to internal validity, such as maturation effects and testing effects, although this study did not involve random assignment of participants (Tenekedjiev et al., 2025).

Research Subjects

The research subjects comprised 60 first-semester students in the Pharmacy Study Program enrolled in the Analytical Chemistry course for the 2025–2026 academic year. The research sample was selected using a purposive sampling technique, given that first-semester students have fulfilled the prerequisites for the Analytical Chemistry course and are in the early stages of developing professional competencies, making them appropriate for developing environmental literacy through Green Analytical Chemistry-based learning (Etikan et al., 2016). The study used two established classes (intact classes) in accordance with the characteristics of the Nonequivalent Control Group Pretest–Posttest design (Stratton, 2019). One class of 30 students was designated as the experimental group, receiving instruction using the Problem-Based Learning model based on Green Analytical Chemistry (PBL-GAC), while the other class of 30 students served as the control group, receiving direct instruction in the Analytical Chemistry course. The treatment was carried out over five meetings, with each meeting lasting 100 minutes, in line with the course load.

The material studied included basic analytical chemistry techniques, the physicochemical properties of drug molecules, acids and bases, instrumental analysis, and oxidation-reduction reactions. Both groups were taught by the same lecturer to minimise differences in treatment caused by variations in teaching styles. In the experimental group, students worked in small groups of 5–6 to solve contextual problems integrating the principles of Green Analytical Chemistry, while in the control group, learning was delivered through lectures, discussions, and practical work aligned with the module, without using GAC-based problem-solving scenarios. Consistency of treatment implementation (treatment fidelity) was monitored using a learning implementation observation sheet completed by two observers at each meeting to ensure that all learning stages were implemented according to the designed syntax.

Research Procedure

The Green Analytical Chemistry-based Problem-Based Learning (GAC-PBL) model was implemented in the experimental group across six structured, interconnected learning stages. The first stage began with an orientation to laboratory environmental problems, in which students were introduced to real-world issues related to the environmental impacts of chemical and pharmaceutical waste, including contamination of water bodies and the ecological risks resulting from improper disposal of these materials (Patel et al., 2024). The second stage involved identifying sources of analytical waste generated by various common laboratory chemical testing procedures, including the use of organic solvents and hazardous reagents, as well as the generation of liquid and solid waste. The third stage was an in-depth investigation into the principles of Green Analytical Chemistry, where students independently studied the twelve GAC principles proposed by (Gałuszka et al., 2013) and applied them to the context of pharmaceutical analysis. The fourth stage required students to develop alternative, more environmentally friendly analytical procedures by applying GAC principles, such as using safer solvents, reducing sample volume, and optimising analytical conditions without compromising the validity or accuracy of test results (Mehta et al., 2024). The fifth stage involves presenting and evaluating each group's solutions with the lecturer and other students, facilitating critical discussion and collaborative concept refinement.

The final stage involves reflecting on the potential environmental impacts of the proposed solutions to strengthen students' awareness of their professional responsibilities as future pharmacists in supporting sustainable laboratory practices. A similar approach has been reported to enhance students' understanding of the environmental impacts of laboratory activities and encourage the application of GAC principles in pharmaceutical analysis practices (Streuli et al., 2025). As an illustration of this model's application, one learning problem is: "How to design a vitamin C analysis procedure that produces minimal waste while still providing accurate results?" This requires students to explore alternative solvents, reduce sample volume, and choose more environmentally friendly detection methods. Throughout the learning process, the lecturer acts as a facilitator, guiding students through inquiry without directly providing solutions, thereby encouraging the development of critical thinking, problem-solving, and independent learning (Barrows, 1996; Hmelo-Silver, 2004).

Research Instrument

The research instrument was an environmental literacy test consisting of 20 multiple-choice questions with 4 answer options each. This instrument was designed to measure four main indicators of environmental literacy, adapted from the environmental literacy framework developed by Roth, (1992) and McBride et al. (2013). The first indicator is environmental knowledge, which includes students' understanding of ecological concepts, environmental issues related to chemical activities, and regulations governing hazardous waste management. The second indicator is environmental attitudes, which reflect students' concern, responsibility, and sensitivity towards environmental sustainability in the context of laboratory practice. The third indicator is environmental problem-solving competence, which measures students' ability to identify, analyse, and critically evaluate environmental problems and formulate appropriate alternative solutions. The fourth indicator is environmental behaviour, which reflects students' tendency to act in environmentally friendly ways, both in laboratory activities and in everyday life (Hollweg et al., 2011; Zsóka et al., 2013).

Table 1. Environmental Literacy Test Questions Design

Environmental Literacy Dimension	Indicator	Number of Questions	Question Number
Environmental knowledge	Understand the concepts of green analytical chemistry, ecology, waste, regulation	5	1 – 5
Environmental attitudes	Concern and responsibility for the environment	5	6 – 10
Environmental troubleshooting	Problem analysis and solution selection	5	11 – 15
Environmental behavior	Implementation of eco-friendly behavior	5	16 – 20

The table 1 shows the distribution of test items based on the four dimensions of environmental literacy that form the basis for the development of the research instrument. Each dimension is represented by five test items, ensuring that all aspects of environmental literacy receive a balanced measure. The environmental knowledge dimension is measured using test items 1–5, which assess students' understanding of Green Analytical Chemistry, ecological principles, laboratory waste management, and environmental regulations. The environmental attitude dimension is measured using test items 6–10, which assess students' levels of concern, responsibility, and commitment to environmental conservation during laboratory activities. The environmental problem-solving competency dimension is represented by test items 11–15, which measure students' ability to identify, analyse, evaluate, and determine solutions to environmental problems related to analytical chemistry practices. Meanwhile, the environmental behaviour dimension is measured using test items 16–20, which assess students' tendency to engage in environmentally friendly behaviour in both laboratory activities and daily life. The compilation of this grid was carried out to ensure that each dimension of environmental literacy is represented proportionally so that the instrument is able to measure the construct of environmental literacy comprehensively in accordance with the framework proposed by Roth (1992), Hollweg et al. (2011), and McBride et al., (2013).

Table 2. The results of the analysis of validity tests, difficulty tests, and different power tests of environmental literacy test instruments

Question No.	Corrected Item-Total Correlation	Criteria	Verdict	P (Difficulty Index)	Difficulty Categories	D (Differential Power Index)	Category (Differentiation)
1	0,468	Valid	Used	0,53	Medium	0,43	Good
2	0,521	Valid	Used	0,60	Medium	0,50	Good
3	0,442	Valid	Used	0,57	Medium	0,39	Good
4	0,575	Valid	Used	0,63	Medium	0,57	Excellent
5	0,487	Valid	Used	0,50	Medium	0,46	Good
6	0,534	Valid	Used	0,47	Medium	0,36	Good
7	0,462	Valid	Used	0,57	Medium	0,43	Good
8	0,603	Valid	Used	0,67	Medium	0,54	Excellent
9	0,515	Valid	Used	0,63	Medium	0,50	Good
10	0,486	Valid	Used	0,53	Medium	0,39	Good
11	0,549	Valid	Used	0,60	Medium	0,46	Good
12	0,458	Valid	Used	0,50	Medium	0,43	Good
13	0,495	Valid	Used	0,57	Medium	0,50	Good
14	0,563	Valid	Used	0,63	Medium	0,57	Excellent
15	0,518	Valid	Used	0,47	Medium	0,39	Good
16	0,477	Valid	Used	0,57	Medium	0,43	Good
17	0,536	Valid	Used	0,60	Medium	0,50	Good
18	0,451	Valid	Used	0,53	Medium	0,36	Good
19	0,586	Valid	Used	0,67	Medium	0,54	Excellent
20	0,509	Valid	Used	0,57	Medium	0,46	Good

Based on the results of the item validity test using Corrected Item–Total Correlation, all questions obtained correlation values between 0.442 and 0.603. This value exceeds the r-table value of 0.361 at the 5% significance level, with a sample of 30 students (df = 28). These results indicate that all questions are significantly related to the total instrument score, thereby consistently measuring the construct of environmental literacy. Furthermore, all Corrected Item–Total Correlation values were also above the recommended minimum limit of 0.30, indicating that each item was declared to have good validity. Thus, all 20 questions met the empirical validity criteria and were declared suitable for use as a research instrument without requiring revision or deletion. These results indicate that the instrument captured the four dimensions of environmental literacy: environmental knowledge, environmental attitudes, environmental problem-solving competencies, and environmental behaviour, making it suitable for measuring the environmental literacy of pharmacy students. The difficulty level analysis results showed that the difficulty index (P) for all test items ranged from 0.47 to 0.67. Based on the difficulty-level criteria, this value falls within the moderate category ($0.30 \leq P \leq 0.70$). This indicates that no item was too easy or too difficult, ensuring that each item had a proportional level of difficulty for respondents. Items with a moderate level of difficulty are considered the most effective because they can measure students' abilities more accurately and provide adequate response variation. Therefore, all 20 test items met the criteria for appropriate difficulty and are suitable for measuring students' environmental literacy. These results also demonstrate that the instrument was designed with a balanced level of difficulty to optimally evaluate students' abilities across the four dimensions of environmental literacy: environmental knowledge, environmental attitudes, environmental problem-solving competencies, and environmental behaviour.

The discriminating power analysis results showed that the discriminating power index (D) for all test items ranged from 0.36 to 0.57. Most of the items were in the good category, while several items, namely questions 4, 8, 14, and 19, were included in the very good category. These results indicate that each item had sufficient ability to differentiate students with high levels of environmental literacy from those with low levels. Items with good discriminatory power indicate that the instrument effectively identifies differences in student abilities, while items in the very good category have higher discriminatory power and are more sensitive in differentiating levels of material mastery. Thus, all 20 items met the criteria for good discriminatory power and were suitable for use as a research instrument without requiring item deletion. These results indicate that the instrument is sufficiently reliable to accurately measure students' environmental literacy in accordance with the research objectives.

Data Analysis

Data analysis in this study was conducted using an inferential statistical approach, beginning with descriptive statistics to describe the distribution of pretest and posttest scores in both research groups. Prior to hypothesis testing, classical assumption tests were conducted, including a normality test using the Shapiro-Wilk method (Shapiro & Wilk, 1965; de Souza et al., 2023), with an acceptance criterion of p-value >0.05. A homogeneity of variance test was conducted using Levene's test to assess whether the variances between the two groups were equal, with an acceptance criterion of p>0.05.

Hypothesis testing was conducted using an independent-samples t-test to compare the mean posttest scores and environmental literacy improvement scores between the experimental and control groups, after ensuring that all assumptions were met. Furthermore, to measure the magnitude of the increase in environmental literacy that occurred in each group, an N-Gain (Normalized Gain) calculation was performed which compared the difference between pretest and posttest scores with the maximum possible score, with improvement categories classified as high ($g > 0.70$), moderate ($0.30 \leq g \leq 0.70$), or low ($g < 0.30$) (Hake & Reece, 1999). The effectiveness of the PBL-GAC model was measured primarily using Cohen's d effect size, which provides a general sense of the magnitude of the treatment effect in practice rather than just statistical significance (Cohen, 1988). Interpretation of Cohen's d values follows established criteria, namely small effect ($d = 0.20$), medium effect ($d = 0.50$), and large effect ($d = 0.80$) (Cohen, 1988). The entire data analysis process was conducted at a significance level of $\alpha = 0.05$ using IBM SPSS Statistics version 25.0 and Microsoft Excel to calculate N-Gain and Cohen's d.

RESULT AND DISCUSSION

The table 3 shows descriptive statistics of the environmental literacy pretest and posttest results for the experimental and control groups. Before the treatment, both groups had relatively equal initial abilities. This is evident from the average pretest score of 51.50 for the experimental group and 51.25 for the control group, with the same minimum score of 45 and maximum score of 60. The pretest standard deviation for the experimental group was 4.58, and for the control group was 4.73, indicating that the variation in students' initial abilities in both groups was relatively homogeneous.

Table 3. Environmental Literacy Data Description

Groups	N	Score minimum		Score Maximum		Standard Deviation		Average		Average N-Gain
		Pretest	Postest	Pretest	Postest	Pretest	Postest	Pretest	Postetst	
Experiment	30	45	80	60	90	4.58	3.56	51,5	85,5	0,7040
Control	30	45	60	60	80	4.73	5.15	51,25	70,75	0,3963

After the treatment, environmental literacy scores increased in both groups, but the increase in the experimental group was greater than in the control group. The average posttest score for the experimental group increased to 85.50, while the control group only achieved 70.75. The maximum score for the experimental group also increased to 90, exceeding the control group's 80. The posttest standard deviation for the experimental group decreased to 3.56, indicating that students' abilities became more evenly distributed after the learning process. In contrast, the standard deviation of the control group increased to 5.15, indicating greater variation in learning outcomes among students. Learning effectiveness is also evident from the N-Gain value. The experimental group obtained an average N-Gain of 0.7040, in the high category, while the control group obtained an N-Gain of 0.3963, in the medium category. These results indicate that the application of the Problem-Based Learning model grounded in Green Analytical Chemistry yields a greater increase in environmental literacy than the direct learning used in the control group. Descriptively, these findings indicate that the learning model used with the experimental group is more effective at improving pharmacy students' environmental literacy.

Table 4. Environmental Literacy Ability Prerequisite Test Results

Uji	Sig.	Remarks
Normality	0,161	Normal
Homogenites	0,792	Homogeneous

Before conducting comparative hypothesis testing with the independent-samples t-test, a series of statistical prerequisite tests was rigorously performed to ensure the validity of parametric inferences. The Shapiro-Wilk normality test results showed a p-value of 0.161 ($p>0.05$), indicating that the N-Gain data on environmental literacy skills were normally distributed and thus met the basic assumptions for parametric comparisons (Mishra et al., 2019; Ghasemi & Zahediasl, 2012). Furthermore, the homogeneity of variance test using Levene's test obtained a significance value of 0.792 ($p>0.05$), confirming that the variances between the experimental and control groups were equal or homogeneous, an important requirement to prevent type I error inflation when using a t-test with pooled variances. By meeting these two classic assumptions, the independent sample t-test is considered statistically valid for testing mean differences between two groups.

Table 5. Analysis of differences in environmental literacy ability

Variable	Df	t-count	Sig.	Cohen's d
N-gain Environmental Literacy	58	19,671	0,000	5,08

Hypothesis testing was conducted to answer the research question regarding the effectiveness of the Green Analytical Chemistry-based Problem-Based Learning model in improving environmental literacy among pharmacy students. Before conducting the hypothesis testing, it was first ensured that all necessary statistical assumptions were met. The Shapiro-Wilk normality test indicated that the environmental literacy post-test data for both groups were normally distributed, with p-values> 0.05 for each group. Levene's test for homogeneity of variance also indicated that the variances between the experimental and control groups were equal, with a p-value > 0.05. With all assumptions met, the hypothesis testing was continued with an independent t-test (Independent Samples T-Test) to compare the average post-test environmental literacy scores between the two groups. The analysis results showed a t-value of 19.671 with 58 degrees of freedom (df). The resulting significance value (Sig.) was 0.000, which was much smaller than the set significance level of $\alpha = 0.05$. Thus, the null hypothesis (H_0), which states that there is no significant difference in environmental literacy between the experimental and control groups after learning, is rejected, and the alternative hypothesis (H_1), which states that there is a significant difference between the two groups, is accepted.

The findings of this study indicate that integrating Problem-Based Learning (PBL) with

Green Analytical Chemistry (GAC) principles creates a more meaningful learning experience than conventional learning, as students not only learn analytical chemistry concepts but also apply them to solve authentic environmental problems. Through problem identification, scientific investigation, collaborative discussion, and evaluation of alternative solutions aligned with GAC principles, students actively construct knowledge while developing critical thinking, decision-making, and a sense of responsibility for sustainability. These findings are consistent with the results of a systematic review by (Varadarajan & Ladage, 2024), which showed that PBL in chemistry learning improves conceptual understanding, problem-solving skills, and the connection between scientific concepts and real-world contexts. The results of this study also align with a meta-analysis by (Anazifa & Djukri, 2017), which reported that PBL positively impacts critical thinking skills and learning outcomes compared to conventional learning. From a green chemistry education perspective, research by Płotka-Wasylka et al. (2023) demonstrated that integrating Green Analytical Chemistry principles into learning can increase awareness of sustainable laboratory practices through reduced use of hazardous chemicals, waste minimisation, and efficient use of resources. Furthermore, research by (Lozano et al., 2017) confirmed that learning that integrates sustainability principles into higher education curricula is more effective in developing sustainability competencies, including changes in student attitudes and behaviours.

The synthesis of these findings suggests that the superiority of GAC-based PBL stems not only from the use of an active learning model but also from the integration of a sustainability context, which enables students to connect scientific concepts to the environmental consequences of each laboratory decision. The combination of these two approaches allows for the development of a more comprehensive dimension of environmental literacy, encompassing knowledge, attitudes, problem-solving skills, and behaviours that support sustainable laboratory practices. Although statistical significance testing has demonstrated a significant difference between the two groups, substantive measurement of treatment effectiveness requires further analysis by calculating an effect size, which indicates the magnitude of the treatment's effect in practice rather than its statistical significance (Cohen, 1988). The effect size calculation in this study used Cohen's d, which measures the mean difference between two groups in units of combined standard deviations. The calculation results showed a Cohen's d value of 5.08. Referring to the interpretation criteria established by Cohen's d (1988), a value of 5.08 falls into the category of a very large effect, as it exceeds the threshold of 0.80 for this category. Thus, the effectiveness of the Green Analytical Chemistry-Based Problem-Based Learning model is not only statistically significant but also has a substantial and practically meaningful impact on improving the environmental literacy of pharmacy students.

This large effect size has important implications for pharmacy education. An effect size of 5.08 indicates that the mean environmental literacy score in the experimental group exceeds that of the control group, which, in an educational context, can be interpreted as a substantial difference with high practical relevance. This significant impact can be attributed to the unique characteristics of the PBL-GAC model, which combines a problem-based pedagogical approach with relevant and applicable GAC content. Through contextually designed PBL scenarios, students not only acquire declarative knowledge about environmental issues but also develop procedural skills in designing environmentally friendly analytical methods, practice critical thinking skills in evaluating the environmental impact of laboratory procedures, and develop pro-environmental attitudes and behaviours through a structured reflection process. These findings provide a strong empirical contribution to the literature on the effectiveness of innovative pedagogies in science and health education, while confirming that integrating sustainability into the pharmacy curriculum is not just talk but has a real, measurable impact.

CONCLUSION

Based on the results of the independent-samples t-test, a significant difference in environmental literacy skills was found between students who received instruction using the

Green Analytical Chemistry-based PBL model and those who received direct instruction without Green Analytical Chemistry. Furthermore, the experimental group demonstrated a higher average N-Gain score than the control group, indicating that implementing the PBL-GAC model led to greater improvements in environmental literacy. This study has several limitations. First, it used a quasi-experimental design with intact classes, thereby pre-assigning participants at random. Second, the study involved only students from a single study program at a single university, so the results require careful interpretation and cannot be generalised broadly. The Green Analytical Chemistry-based Problem-Based Learning model has been shown to be effective in improving environmental literacy among pharmacy students. The experimental group demonstrated greater improvements in environmental literacy than the control group, with high N-Gain scores and a large effect size. Integrating Green Analytical Chemistry principles into analytical chemistry instruction is recommended as a learning strategy to support sustainable pharmacy education. Future research is recommended to involve larger, more diverse samples from multiple universities, employ a more robust experimental design, and evaluate the long-term impact of implementing a Green Analytical Chemistry-based PBL model on pharmacy students' environmental literacy and professional competency.

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