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Improving students' critical thinking abilities and environmental sensitivity through project-based learning integrated with green chemistry principles

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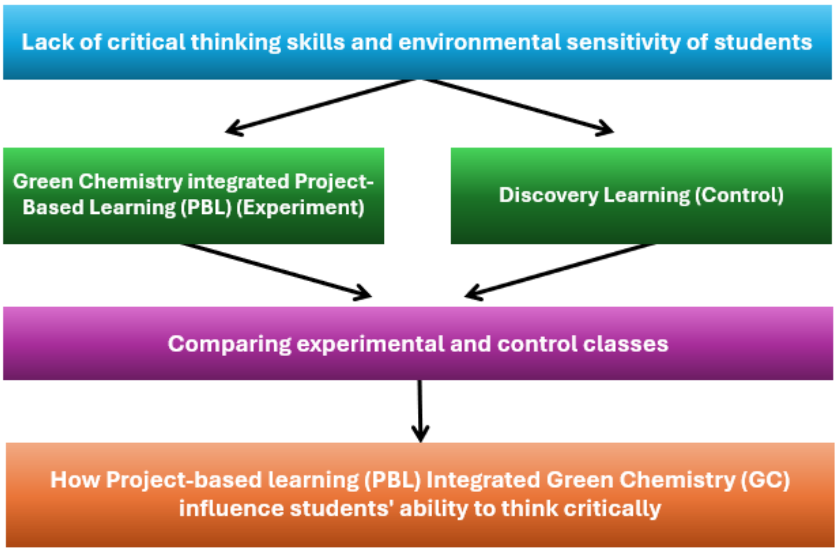
Abstract

This quasi-experimental research seeks to examine the impact of the Project-Based Learning (PBL) model integrated with Green Chemistry (GC) on students' critical thinking abilities (CTA) and environmental sensitivity (ES) at chemical equilibrium. A Randomized Post-test-Only Control Group design was used in four classes of Class XI F students at SMAN 1 Gowa, South Sulawesi as the population. The samples were classes XI F1 and XI F4, each consisting of 36 students, taken randomly. CTA data was obtained with seven essay questions which have been tested with quite high reliability (0.68). The ES questionnaire consists of 25 statements. Testing with the Independent Sample t-test shows that the integrated PBL GC Model influences increasing student CTA. The Wilcoxon test results also show that the application of the GC-integrated PBL model affects increasing students' ES. This research implies that it is hoped that teachers will continue to integrate green chemistry in learning continuously to support sustainability programs.



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Highlights

- Developing Critical Thinking Abilities through complex problem-solving.
- Developing CTA through critical analysis of environmental impacts.
- Environmental sensitivity: green chemistry principles in the learning process.
- Project-based learning (PBL) integrated with green chemistry (GC) enhances ES.
- PBL with GC encourages active involvement in understanding concepts.

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1. Introduction

One of the competencies students need to face 21st-century challenges is critical thinking skills (Mitarlis *et al.*, 2023). This ability prepares students to compete in the world of work (Thornhill-Miller *et al.*, 2023). Critical thinking skills help students evaluate and reflect on facts and data; they are not limited to solving academic problems (Huber and Kuncel, 2016; Tabanelli *et al.*, 2021). The same thing was also expressed by Van Brederode *et al.* (2020), where students' critical thinking skills in chemistry are related to understanding information in depth and making decisions based on careful consideration. Critical thinking skills help students become independent and responsible learners to help prepare students for changes that occur in society (Rimienė, 2002).

Students' critical thinking skills can foster environmental sensitivity to support sustainability programs. Students' environmental sensitivity can be fostered by providing understanding and familiarization related to the principles of green chemistry (GC) (Pluess, 2015). Green chemistry practices in everyday life can be instilled through a habituation process, for example reducing the use of plastic packaging, choosing safer materials, reducing waste, and using energy efficiently in chemistry learning/experiments (Aubrecht *et al.*, 2019). This contributes to environmental sustainability and the achievement of SDGs (Koulougliotis *et al.*, 2021).

Several studies have explored the link between learning materials and environmental issues, especially the need to apply green chemistry principles, thereby increasing environmental sensitivity (Santosa, 2023). Green chemistry principles integrated into education can increase students' sensitivity to environmental issues and encourage environmentally conscious behavior (Koulougliotis *et al.*, 2021). Green chemistry is integrated into the school curriculum, primarily through practical activities to increase students' awareness and involvement in improving environmental sustainability (Chen *et al.*, 2020). Integrating green chemistry into education not only enhances students' environmental awareness but also fosters their critical thinking skills. Through this approach, students learn about the importance of sustainable practices in chemistry and develop critical evaluation, reflection, and decision-making skills. Education that combines green chemistry and critical thinking skills can help create a more environmentally conscious generation that can face future challenges and contribute to sustainable development.

The development of students' critical thinking skills is considered an important step in achieving educational goals holistically, including learning goals with the independent curriculum in Indonesia (Pahrudin *et al.*, 2021). However, in reality, the development of students' critical thinking skills in Indonesia is still not optimal in terms of the role of teachers and supporting infrastructure (Khalid *et al.*, 2021). The learning paradigm does not emphasize students' ability to find out, formulate problems, think analytically, work together, and collaborate in solving problems. Critical thinking skills are very important for students because they enable them to solve problems (Basri *et al.*, 2019); and explain the reasons for solving problems (Shanta and Wells, 2020). Critical thinking will make students open-minded (Abrami *et al.*, 2015) and reflective thinking (Ennis, 2015).

Factors contributing to low critical thinking skills include the use of learning methods that do not actively involve students and emphasize memorization rather than investigation (Solihati and Hikmat, 2018). Direct teaching strategies, place the teacher as the focus (Sarwanto *et al.*, 2021). Students' self-efficacy in expressing ideas and low interest in learning (Hyytinen *et al.*, 2018). The low critical thinking skills of students in chemistry material were also reported by Purwanto *et al.* (2022). Furthermore, research indicates that Indonesian students' environmental sensitivity also requires significant improvement (Situmorang *et al.,* 2020).

Environmental sensitivity is an important aspect that needs to be studied because it plays a significant role in determining an individual's response to changes in environmental conditions. Research shows that environmental sensitivity affects how individuals process and respond to information from the environment (Pluess, 2015). In addition, it plays a vital role in shaping pro-environmental attitudes and behaviors. Individuals with high environmental sensitivity tend to be more aware of the impact of their actions on the environment and are more motivated to take responsible actions, such as recycling, saving energy, or reducing plastic use. Research shows that environmental sensitivity mediates the relationship between environmental knowledge and intention to behave pro-environmentally (Bala *et al.*, 2023). Environmental sensitivity can provide insights into developing more effective educational policies and intervention programs. By understanding the factors that influence environmental sensitivity, policymakers can design more focused and impactful educational programs, which will encourage future generations to be more actively involved in environmental protection (Kyriakopoulos *et al.*, 2020).

Efforts to overcome the low critical thinking skills and environmental sensitivity in students have been made, including by using a student-centered learning model that can provide meaningful learning experiences (Minan *et al.*, 2021). Chemistry learning is very possible by contextualizing the concepts being learned (Abdurrahman *et al.*, 2019). The PBL model was chosen as one of the learning models because it can improve student understanding and contribute to increasing environmental sensitivity (Hanifha *et al.*, 2023).

The PBL model is a student-centered learning model that provides meaningful learning experiences and produces products (Suradika *et al.*, 2023). PBL allows students to plan learning activities, carry out collaborative projects, and ultimately produce work products that can be presented. Experiences and concepts are built based on products produced in the project-based learning process. PBL is an innovative learning model that emphasizes creativity and problem-solving and provides students with opportunities to improve critical thinking and collaborative skills (Grossman *et al.*, 2019). PBL has been shown to increase student motivation and engagement if learning is integrated with the principles of GC (Mitarlis *et al.*, 2023). PBL, compared to conventional methods, is effective in increasing class participation and providing a real-world learning context (Almulla, 2020). Implementing PBL can improve students' abilities in terms of critical thinking, collaboration, environmental awareness, critical and creative thinking, social, emotional, collaborative, and problem-solving abilities (Mora *et al.*, 2020).

Critical thinking skills are not only applied in the learning process but can be reflected in students' environmental care attitudes. In the context of everyday life, critical thinking skills are needed to maintain environmental sustainability. The contextual meaning of critical thinking is how to maintain the environment so that it is useful for the present and the future (Amin, *et al.*, 2020).

This study analyzes the effect of implementing the GC-integrated PBL model on the critical thinking skills and environmental sensitivity of high school students. The main material of the study is the concept of chemical equilibrium by considering its characteristics related to everyday concepts. For example, the concept of dynamic equilibrium; factors that affect the chemical equilibrium system; the human blood equilibrium system related to blood pH regulation. This study has a novelty, namely integrating the principles of green chemistry into chemistry learning through teaching modules. This makes a significant contribution because it is very relevant to global issues, namely the issue of environmental quality which is currently a concern. To deal with this issue, of course, a positive attitude is needed from students including environmental sensitivity and critical thinking. Both are closely related because it is hoped that students who have high critical thinking skills will implement them in dealing with environmental problems. In Indonesia, several studies on PBL integrated with green chemistry in the learning process. However, there are still few that link it to students' environmental sensitivity (Amin *et al.,* 2020). Thus, it is very urgent to explore. On the other hand, the curriculum related to the application of green chemistry in schools is inadequate. Through this PBL, by inserting the habituation of attitudes related to the principles of GC, this is urgently built-in for students considering the phenomenon of shifting student characters including student insensitivity to the environment. This supports global efforts to promote sustainability (Sustainable Development Goals (SDGs)) through the education or learning process.

2. Experimental methods

2.1. Method

The research design used was a comparative study of two independent groups. The design used was a Randomized post-test Control Group. The population of the study was four classes of students in grade XI F. The sample was taken randomly using the lottery technique, and two classes, XI F1 and XI F4 were selected, each with 36 students. The experimental class implemented the PBL model, while the control class implemented the discovery learning (DL) learning model. The instrument used was a structured essay test with seven items on the concept of chemical equilibrium. This instrument reveals critical thinking skills in the aspects of interpreting, analyzing, deducting, inferring, and evaluating. Content validation of the instrument device was carried out by two chemical education experts. Gregory (2007) stated that a content validity examination was carried out to test the accuracy of critical thinking ability indicators for the items that had been created. The data were analyzed using the independent sample t-test because the two samples were independent of each other. This test was chosen because based on the prerequisite test results, the normality test with Kolmogorov Smirnov showed that both experimental groups had normal distribution (the value of 0.2 is greater than the significance value of 0.05). The homogeneity test with Levene statistic obtained a significance value of 0.054, meaning that the variance of both groups was homogeneous.

The Environmental Sensitivity Questionnaire (ESQ) employed in this study is based on the instrument developed by Jusniar *et al.* (2023). The questionnaire comprises four indicators, totaling 25 items, and demonstrates a reliability coefficient of 0.792, indicating a high level of internal consistency. The four aspects assessed by the ESQ are:

1. Harmony of life and diversity
2. Environmental balance
3. Interdependence
4. Sustainability

Three of the twelve Green Chemistry Principles (GCP) are associated with these aspects:

- Preventing waste (GCP 1)
- Increasing energy efficiency (GCP 6)
- Minimizing the potential for accidents (GCP 12)

Responses to the ESQ were measured using a four-point Likert scale:

- Strongly Agree (SA)
- Agree (A)
- Disagree (DA)
- Strongly Disagree (SDA)

2.2. Research procedure

Pre-test: A pre-test was conducted to determine students' initial abilities before being given treatment.

Treatment: The experimental class was given project-based learning (PBL) integrated with Green Chemistry, while the control class received learning with the DL Model. Implementation of control and experimental class learning as in **Table 1** and **Table 2**.

Table 1. Control and experimental class learning syntax.

Integrated PBL Stages GC Principles	DL Stages
Basic questions (Integrating GC principles)	Stimulation
Design a plan for the project (Integrating GC principles)	Formulating problems
Develop a schedule	Collecting data
Monitor Progress	Processing and analyzing data
Present and test the design results (Integrating GC Principles)	Verifying
Evaluate the learning experience	Generalizing

Source: Elaborated by the authors.

Table 2. Synthesis of critical thinking skills from several theories.

Ennis (2015)	Krulik *et al*. (1995)	Facione (1990)	Synthesis Result
Providing simple explanations Building basic skills	Identifying and Interpreting information	Interpretation: clarifying meaning through categorization and translation	Interpretation
Summarizing	Analyzing information	Analysis: Identifying and examining	Analysis
Providing advanced explanations Organizing strategies and technique	Evaluating evidence and arguments	ideas, arguments, or procedures Self-regulation: Self-assessment and reflection	Inferences Deduction/Evaluation

Source: Elaborated by the authors.

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The instruments used in this study to assess critical thinking ability (CTA) comprise five core components (Ennis, 2015):

Interpretation: involves the selection of relevant information or knowledge and the clarification of meanings within specific provisions, facts, and informational content.

Analysis: refers to the identification of the constituent elements of a situation and the examination of their interrelationships.

Inference: encompasses the synthesis of available evidence, the formulation of alternatives, and the drawing of logical conclusions.

Evaluation: pertains to the assessment of the credibility of information sources, the validity of claims, and the critical appraisal of arguments and assumptions.

Deduction: involves the formulation of reasoned judgments based on logical processes in which conclusions depend on sound deductive reasoning skills.

In the experimental class, the project designed in the form of posters is embedded with slogans that can accustom students to care and be sensitive to the environment. For example, the words "save energy"; "save our earth" and others. In the learning process, teachers instill habits that can have an impact on environmental sustainability. For example, in the initial motivation section, the teacher appeals to use drinking water tumblers to minimize plastic waste.

Post-test: After treatment, a CTA test is given to measure critical thinking abilities. Apart from that, students' environmental sensitivity questionnaires were also given after four learning meetings were completed.

2.3. Data analysis

The critical thinking ability data obtained were analyzed using parametric statistical tests, namely the Independent Sample t-test to compare the average between the experimental group using the Green Chemistry integrated PBL model and the control group with the DL model. The normality test was carried out using the Kolmogorov-Smirnov method, and the homogeneity test was carried out using Levene Statistic to ensure that the data was normally distributed and the variance between groups was homogeneous.

3. Results and discussion

The instrument is tested for validity and reliability before use. Testing of content validity and construct validity is carried out and assessed by experts (validators). Content validity refers to the extent to which an instrument or test covers representatively all aspects of the domain to be measured. Meanwhile, construct validity involves the extent to which the instrument measures the intended construct or concept following the underlying theory or conceptualization. The results of the validity test by experts (two chemistry education experts and 2 practitioners) concluded that the critical thinking skills test instrument used met the criteria for being very valid, with an average inter-rater consistency of 97.6%. Thus, it can be used to measure students' critical thinking skills. Apart from the validity test, a reliability test was also carried out using internal consistency via Cronbach's Alpha. This test aims to assess the extent to which a test can provide consistent and reliable results. Reliability measures how well a measurement instrument can produce stable or consistent scores if measurements are taken repeatedly. The reliability testing technique on this CTA instrument test obtained was 0.68, which indicates that the reliability of the CTA instrument is quite good. This reliability value is considered sufficient with a moderate and quite reliable level (Creswell, 2000). The results of the study are presented sequentially, namely the CTA test prerequisite test, the Hypothesis test to determine the effect of the PBL model on students' CTA, and the hypothesis test to determine the effect of implementing the PBL model on environmental sensitivity.

3.1. CTA prerequisite test results

The results of the analysis requirement test consist of a normality test and a homogeneity test. The results of the normality test are shown in **Table 3**.

Table 3. Results of normality test.

Class	sig	Mean	SD
Control	0.200	67.89	8.23
Experiment (PBL)	0.200	75.39	5.95

Source: Elaborated by the authors.

Based on the data in the table above, the sig value (2-tailed) is 0.200, because sig > 0.05, we do not have enough evidence to reject the null hypothesis. Therefore, we can assume that the data from the student's critical thinking ability test results are normally distributed. With the results of this normality test, data analysis can be continued using parametric statistical tests, in this case, the independent t-test to compare the averages between different groups. Homogeneity testing as a prerequisite test is then carried out using Levene statistics. The test results obtained a significance value of 0.054, meaning that the variance of the two groups is homogeneous.

3.2. Hypothesis test results

The calculation results for the hypothesis test can be seen in **Table 4**.

Table 4. Independent sample t-test.

CTA PBL-DL	F	sig	t	df	Sig.	Mean difference	SE
Equal variance assume	3.833	0.054	4.430	70	0.000	7.50	1.69
Equal variance not assume			4.430	63.71	0.000	7.50	1.69

Source: Elaborated by the authors.

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Based on the table of t-test results above, it can be concluded that there is an influence of the PBL model on students' critical thinking skills in chemistry subjects. This is proven by the probability value that gets a score below 0.05 and the average value of the critical thinking test score in the class using the PBL model is significantly different compared to the control class using the DL model.

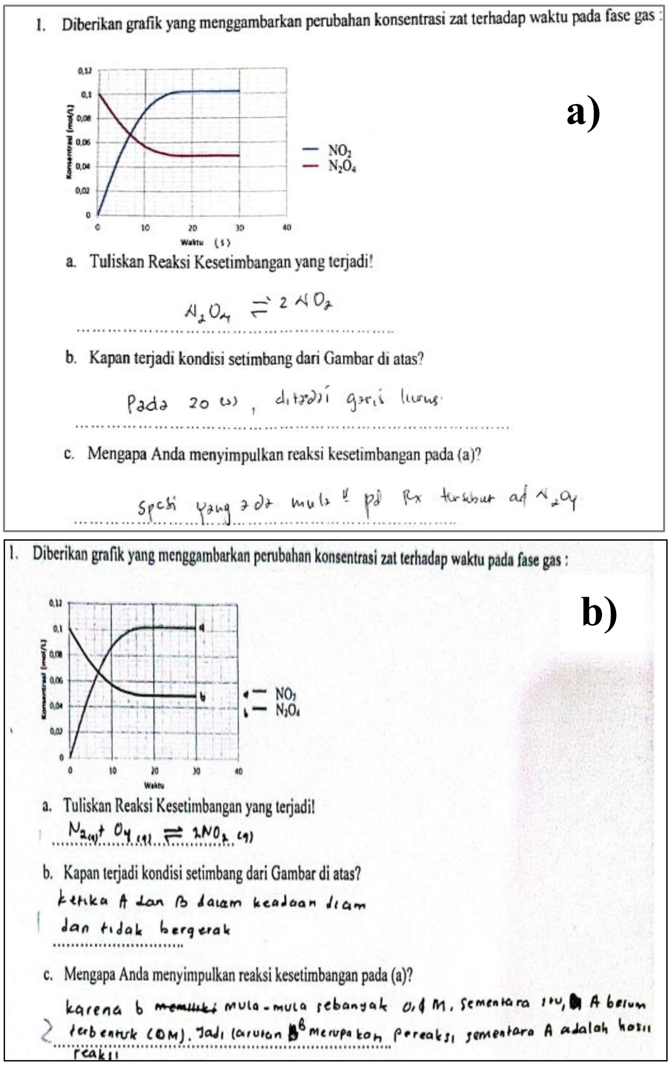

Figure 1. Documentation of Student Answers to Question No. 1. **(a)** correct answer **(b)** wrong answer.
Source: Elaborated by the authors.

Data interpretation is an important process that involves analyzing, organizing, and understanding data to draw meaningful conclusions and make informed decisions. The answer shown in **Fig. 1a** shows that the student was able to interpret the graph that the initial species N_2O_4 and NO_2 are equilibrium products. Equilibrium conditions can be determined at 20 minutes with the characteristic that the graph is flat, meaning that there is no more change over time. The interpretation for the answer to point c is that the equilibrium reaction occurs because macroscopically, there is no more change, but microscopically, the reaction is still ongoing; only the rate towards the formation of NO_2 gas is the same as the rate of decomposition back into N_2O_4 gas. This includes extracting important information, identifying patterns and understanding the implications of the data. Through this process, individuals and organizations can gain valuable insights, identify opportunities, detect potential risks, and evaluate the effectiveness of strategies or interventions.

Data interpretation is not only a technical process but also a social process because it requires access to experiences that enable the use of all meaning-making features (Zagallo *et al.*, 2016). In the picture above on the right, you can see the students' ability to interpret and analyze data in the form of a graph of the equilibrium reaction given. This thinking ability is a key aspect of critical thinking. From the answers given, not only can we see the students' ability to understand the concept of chemical equilibrium but also their ability to analyze information, solve problems, interpret information carefully, and make logical conclusions. In contrast to the student's answer shown in the picture on the left, it can be seen that the student was unable to write the reaction correctly and was unable to describe and interpret the graph related to the conditions for equilibrium to occur. Several studies have shown that students who do not have a good level of scientific reasoning may have difficulty with tasks such as data interpretation and presentation (Coll *et al.*, 2006; Hartmann *et al.*, 2015).

The interpretation of the answer on the right is not entirely correct for point (c) when students are asked to conclude why the reaction at time (b) is categorized as an equilibrium reaction. The correct answer should be that in the sixth minute of the reaction, the reaction rate towards the product (SO3) is the same as the reaction rate of the formation of the reactants (SO_2 and O_2). The ability to draw conclusions is an important component of critical thinking. In the context of critical thinking, inference refers to the ability to draw logical conclusions based on available information and evidence.

This skill is essential for evaluating arguments, making decisions, and solving problems. Several studies have highlighted the importance of inference as one of the main indicators of critical thinking skills. For example, a study that emphasizes the importance of inference as one of the five indicators of critical thinking skills, alongside interpretation, analysis, explanation, and evaluation (Sutama *et al.*, 2022). Likewise, this study identifies inference as one of the six indicators of critical thinking skills, along with interpretation, analysis, evaluation, explanation, and self-regulation. Furthermore, it underlines the inclusion of inference as part of the indicators of critical thinking skills, along with the ability to analyze, evaluate, and make decisions (Hall and Barnes, 2016).

These findings collectively highlight the consensus on the importance of inference as a fundamental aspect of critical thinking skills. From **Fig. 2a**, the evaluation and inference skills of students can be seen. From the answers given, it can be seen that students can understand concepts well and connect various concepts and ideas to create strong arguments. It is also seen that students have good analytical and interpretation skills, indicating that students' critical thinking skills are well-honed. This is different from **Fig. 2b**, where students' evaluation and inference skills are lacking. Several studies have shown that students' poor evaluation and inference skills can be caused by various factors, including cognitive aspects, lack of problem-solving skills related to scientific reasoning skills, poor memory, integration failure, and inability to integrate mathematical constructions into scientific content (Coleman *et al.*, 2023).

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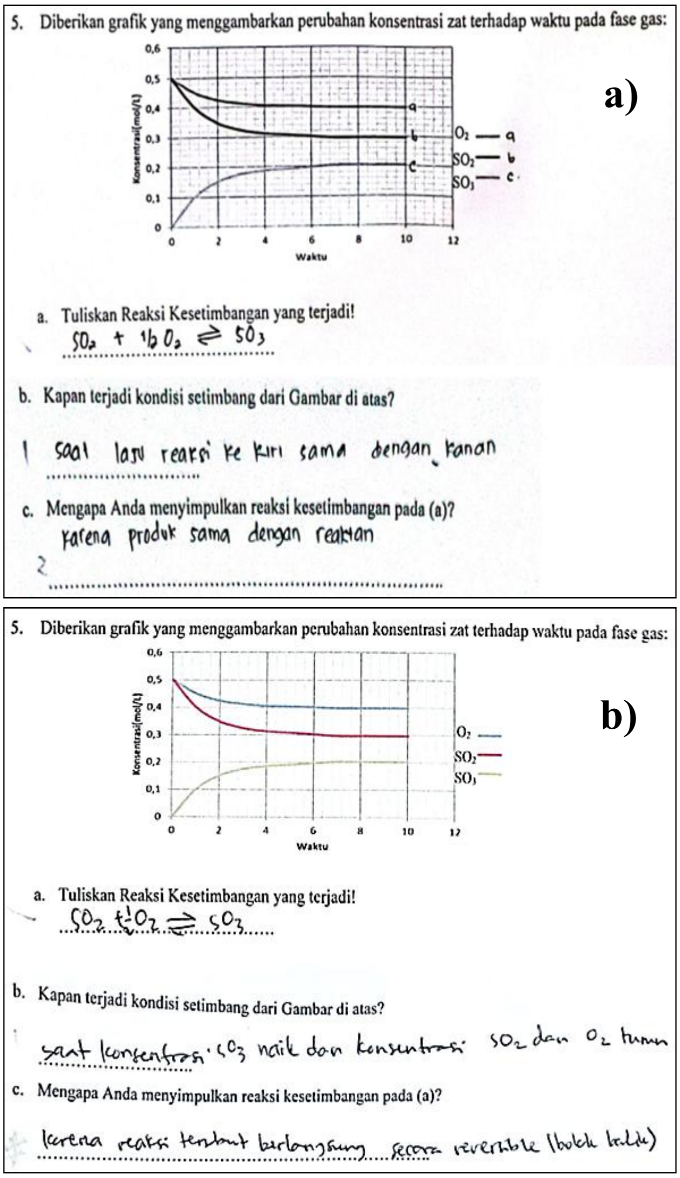

Figure 2. Documentation of Student Answers to Question No. 5. **(a)** correct answer and **(b)** wrong answer.
Source: Elaborated by the authors.

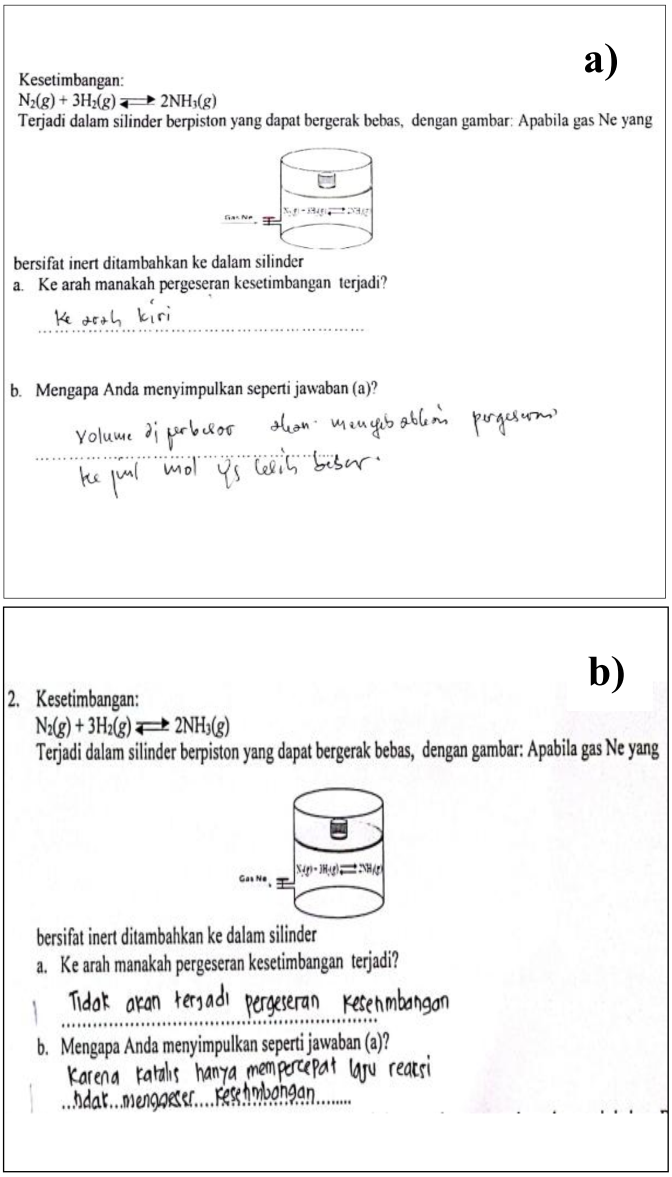

Figure 3. Documentation of Student Answers to Question No. 2. **(a)** correct answer and **(b)** wrong answer.
Source: Elaborated by the authors.

In **Fig. 3a**, students' ability to interpret and analyze data in the form of a given equilibrium reaction graph can be seen. This thinking ability is a key aspect of critical thinking. From the answers given, not only can students' ability to understand the concept of chemical equilibrium be seen, but also their ability to analyze information, solve problems, interpret information carefully, and make logical conclusions. In addition to interpretation skills, students' inference skills can also be seen in the students' answers above. It is proven that students can make logical conclusions based on existing information and understanding related to the concept of chemical equilibrium. Connecting various information and evidence that then underlies decision-making is an integral part of critical thinking skills.

Figure 3b shows students' lacking abilities in terms of interpretation, inference, and customary analysis. Several source indicate that poor data interpretation and analysis by students can be caused by various factors, including lack of strategic knowledge, differences in text or information processing, test anxiety, and the impact of internal and external factors on students' academic performance. as well as scientific research skills (Pols *et al.*, 2021; Wu *et al.*, 2022).

The effectiveness of the implementation of the PBL model can also be proven through documentation of student work results after completing the critical thinking ability test. From the documentation results above, we can see the answer patterns that show their ability to analyze information, link different relevant concepts, and formulate argumentative thinking or problem-solving. The image above also shows students' ability to organize and communicate their ideas clearly and structure.

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Through this documentation, teachers can use it as a very useful evaluation tool to detail and describe students' achievements in developing their critical thinking skills during a certain learning period.

The results above prove the effectiveness of the PBL model in improving students' critical thinking skills. Students who receive learning using the PBL model, their learning patterns tend to make students think more broadly. This is inseparable from the advantages of the PBL model, which hones creative thinking skills, self-regulated learning skills, and self-evaluation (Jansson *et al.*, 2015).

Project learning involves investigation and problem-solving. By assigning projects, students are trained to analyze, synthesize, and critically evaluate a problem so that the peak of the activity is that students can create work (Sutama *et al.*, 2022). Project-based learning makes learning more independent, improves critical thinking and analytical skills, and increases learning interest (Cortázar *et al.*, 2021). The PBL model also fosters collaboration, engages and motivates students, enhances content knowledge, and meets the needs of students with different skills and learning styles, thereby improving student engagement and chemistry learning outcomes (Mebert *et al.*, 2020; Domenici, 2022).

In addition, PBL has been shown to have a positive influence on the development of soft skills and environmental awareness in students, indicating its holistic impact on students' professional and personal growth (López and Palacios, 2024). Furthermore, integrating micro-project-based learning in chemistry has been shown to improve conceptual understanding and essential learning skills across disciplines, highlighting the interdisciplinary benefits of PBL (Tian *et al.*, 2023).

The Green Chemistry integrated PBL model not only provides students with a better understanding of chemical concepts but also broadens their horizons about Green Chemistry and its principles. This model supports sustainable development goals through education (Mitarlis *et al.*, 2023). This article makes a major contribution to improving critical thinking skills and forming environmental sensitivity characters for students who certainly take part in the goals of sustainable development.

3.3. Environmental sensitivity

The Wilcoxon test for Overall and each of the four aspects of environmental sensitivity are presented in **Table 5**.

Table 5. Environmental sensitivity test results.

Test Results	Environmental Sensitivity	Aspect 1 (Harmony of life and diversity)	Aspect 2 (Environmental balance)	Aspect 3 (Interdependence)	Aspect 4 (Sustainability)
Z	−4.800	−4.128	−4.234	−2.762	−3.976
Sig. (2-tailed)	0.000	0.000	0.000	0.006	0.000

Source: Elaborated by the authors.

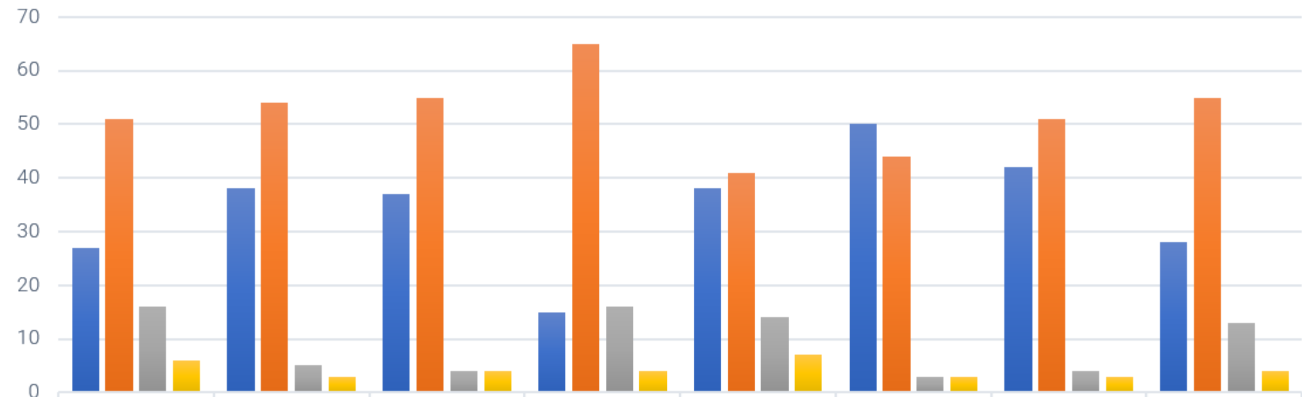
The diagram in **Fig. 4** shows the results of a survey or study comparing two groups of students, the control group and the experimental group, using Project Based Learning integrated with Green Chemistry. Some aspects measured in this environmental sensitivity survey include Harmony of Life, Diversity, Environmental Balance, Interdependence, and Sustainability measured using a Likert scale, namely Strongly Agree (SA), Agree (A), Disagree (DA), and Strongly Disagree (SDA). In the aspect of harmony of life and diversity in the experimental class, there was a significant increase in the categories of 'Strongly Agree' (SA) and 'Agree' (A) for this aspect, with values reaching 38% and 54% respectively for "Harmony of Life," and 50% and 44% for "Diversity." This shows that students involved in PBL integrated with Green Chemistry have a better understanding of the importance of harmony in life and environmental diversity. This finding is in line with research conducted by Amin *et al.* (2022) where the PBL model integrated with the Green Chemistry vision not only improves their conceptual understanding of chemistry but also strengthens their awareness of the need for harmony between human activities and environmental sustainability. Learning activities such as observing and taking real actions, especially in the surrounding environment, can increase environmental sensitivity and student involvement in environmental problems that occur (Amin *et al.*, 2022; Hanifha *et al.*, 2023).

In contrast, in the control group, the percentage of 'Strongly Agree' (SS) only reached 27% for "Harmony of Life" and 38% for "Diversity," indicating a lower understanding of these concepts compared to the experimental group. The increase in understanding in the experimental group was due to students gaining direct experience in environmental-based projects that were relevant to real contexts, which is a characteristic of the PBL model.

In the aspect of environmental balance and interdependence, the 'Agree' (S) response in the experimental group for "Environmental Balance" reached 55%, higher than the control group, which was only 51%. This increase reflects that project-based learning allows students to better understand the interdependence between humans and the environment and the importance of maintaining ecological balance. The increase in the percentage of 'Strongly Agree' and 'Agree' in the experimental group also shows that students are becoming more aware of the importance of sustainable behavior and how individual actions can affect the balance of the ecosystem as a whole.

In the aspect of "Sustainability," there was an increase in environmental awareness in the experimental group, with 42% of students answering, 'Strongly Agree' and 51% answering 'Agree'. In contrast, the control group only had 28% who answered, 'Strongly Agree' and 55% who answered 'Agree'. This indicates that the integration of Green Chemistry in PBL can improve students' understanding of sustainable development goals (SDGs) and the importance of protecting the environment for future generations.

This finding is in line with Mitarlis *et al.* (2023), which shows that the integration of green chemistry principles in basic chemistry learning can support the achievement of SDGs. This approach has been shown to contribute to students' understanding of the concept of sustainability and has a positive impact on students' behavior in protecting the environment (Amin *et al.*, 2020). The results of the study showed that the experimental group involved in PBL integrated with Green Chemistry was better able to understand and apply critical concepts related to the environment, such as harmony of life, diversity, environmental balance, and sustainability. This is because PBL requires students to think critically, analyze problems, evaluate various options, and find innovative, data-based solutions to real environmental challenges. In line with these findings, Issa and Khataibeh (2021) stated that PBL could not only improve conceptual understanding and critical thinking but can also make students creative and communicative, dare to make decisions and have learning independence. The integration of Green Chemistry in PBL allows students to learn through direct experience, which increases their sensitivity to the environmental impacts of various human activities. The data in the diagram shows that students who learn through PBL have more positive responses to aspects of sustainability, indicating increased sensitivity to environmental issues.



	Harmony of life and diversity	Environmental balance	Interdependence	Sustainability	Harmony of life and diversity	Environmental balance	Interdependence	Sustainability
	control (%)				Experiment (%)			
SS	27	38	37	15	38	50	42	28
S	51	54	55	65	41	44	51	55
TS	16	5	4	16	14	3	4	13
STS	6	3	4	4	7	3	3	4

Figure 4. Description of environmental sensitivity in the control and experimental classes.
Source: Elaborated by the authors.

3.4. Research limitations

This research was conducted limitedly in one school so that other researchers could continue it on a larger scale. The project-based learning model applies the habituation method to integrate GC principles into learning. Further researchers can apply other learning that integrates green chemistry to socialize and support sustainability through education. Further researchers can explore the same thing at various levels of education or integrate technology to support the GC-integrated PBL learning model.

4. Conclusions

In this research, it was found that there was an influence of implementing the PBL model integrated with GC principles on critical thinking skills and environmental sensitivity. These two aspects of ability and character of environmental sensitivity are very important in dealing with global problems related to the environment in the world. Environmental conditions that are not good certainly need to receive serious attention in various fields, especially the education sector, to support sustainability. Thus, it is recommended for teachers and policymakers to always integrate green chemistry into learning and the curriculum to support sustainability.

Authors' contribution

Conceptualization: Jusniar Jusniar; Dewiyanti Fadly; **Data curation**: Army Auliah; Jusniar Jusniar; **Formal Analysis**: Jusniar Jusniar; Army Auliah; **Funding acquisition**: Jusniar Jusniar; Syamsidah Syamsidah; **Investigation**: Jusniar Jusniar; Dewiyanty Fadly; **Methodology**: Syamsidah Syamsidah; Jusniar Jusniar; **Project administration**: Jusniar Jusniar; Dewiyanti Fadly; **Resources**: Jusniar Jusniar; Army Auliah; **Software**: Not applicable. **Supervision**: Jusniar Jusniar; Syamsidah Syamsidah; **Validation**: Jusniar Jusniar; Army Auliah; **Visualization**: Dewiyanti Fadly; **Writing – original draft**: Jusniar Jusniar; Dewiyanti Fadly; **Writing – review & editing**: Jusniar Jusniar; Dewiyanti Fadly.

Data availability statement

The data will be available upon request.

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Conflict of interest

The authors declare that there is no conflict of interest.

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