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Enhancing Science Literacy and Critical Thinking Through Project-Based Chemistry Labs with Natural Materials

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Abstract

The present study by investigating an alternative approach integrating natural materials to create more contextual and meaningful learning experiences. A quasi-experimental design was employed, with the experimental group engaging in hands-on laboratory projects using natural indicators such as purple cabbage extract, eggshell waste, and vinegar, while the control group received conventional instruction. Independent t-test analysis revealed a significant difference between the groups, with the experimental group outperforming the control group in post-test assessments of scientific literacy and critical thinking. These findings indicate that incorporating environmentally friendly, context-based materials into chemistry education could effectively enhance essential skills. Moreover, the project-based approach encouraged students to apply scientific concepts, think critically, and relate their learning directly to everyday life.

Keywords: critical thinking; natural materials; scientific literacy

Abstrak

Penelitian ini mengkaji pendekatan alternatif yang mengintegrasikan bahan-bahan alami untuk menciptakan pengalaman belajar yang lebih kontekstual dan bermakna. Desain kuasi-eksperimental digunakan, dengan kelompok eksperimen terlibat dalam proyek laboratorium praktik menggunakan indikator alami seperti ekstrak kubis ungu, limbah kulit telur, dan cuka, sementara kelompok kontrol menerima pembelajaran konvensional. Analisis uji-t independen menunjukkan perbedaan yang signifikan antar kelompok, dengan kelompok eksperimen mengungguli kelompok kontrol dalam penilaian pasca-tes literasi sains dan berpikir kritis. Temuan ini menunjukkan bahwa menggabungkan bahan berbasis konteks yang ramah lingkungan ke dalam pendidikan kimia dapat secara efektif meningkatkan keterampilan esensial. Lebih lanjut, pendekatan berbasis proyek mendorong siswa untuk menerapkan konsep-konsep ilmiah, berpikir kritis, dan menghubungkan pembelajaran mereka secara langsung dengan kehidupan sehari-hari.

Keywords: bahan alami; berpikir kritis; literasi sains

Introduction

Chemistry education in secondary schools plays a crucial role in equipping students with logical and analytical thinking skills, as well as the ability to understand natural phenomena scientifically (Pujawan et al., 2022). Critical thinking enables students to analyze information, ask meaningful questions, and construct evidence-based arguments (Sari et al., 2025). It refers to the capacity to think logically and reflectively, with a focus on determining what is credible and identifying the most appropriate course of action ('Aisy, 2023). In Indonesia, these skills are considered a top priority in educational development, serving as an essential foundation for cultivating high-quality human resources. Critical thinking skills are widely regarded as indicators of individual success and intelligence (Dewi et al., 2025).

Key characteristics of individuals with strong critical thinking skills include 1) striving for clarity in every statement, 2) identifying accurate information, 3) using reliable sources and citing them appropriately, 4) maintaining consistency and relevance to the subject matter, 5) being open to diverse perspectives, and 6) thinking systematically and structurally when solving problems (Nisak & Ardhana, 2023).

Critical thinking is one of the primary objectives in school learning, as it integrates various learning experiences to help students understand concepts comprehensively and in alignment with learning goals. Individuals with critical thinking skills can better regulate emotions, think rationally, address problems effectively, and develop appropriate solutions.

Meanwhile, scientific literacy reflects students' understanding of scientific concepts and their ability to apply them in daily life. It encompasses the capacity to comprehend scientific principles, communicate them effectively, and use such knowledge to solve real-world problems (Aryani et al., 2022). Scientific literacy also fosters a caring and responsive attitude toward the environment. It is crucial for enabling individuals to evaluate scientific issues and assess the benefits and risks of scientific developments (Vashti et al., 2020). By developing scientific literacy, communities are better equipped to address complex social and environmental challenges in the modern era, particularly those linked to advances in science and technology (Doloksaribu & Suaka, 2021).

Despite its importance, chemistry education in schools often remains heavily theoretical, offering limited opportunities for students to develop these competencies to their full potential. Conventional teaching approaches tend to render students passive, limiting their engagement and exploration of knowledge. Consequently, active, contextual, and student-centered learning models are required to overcome this issue.

One effective strategy is laboratory-based project learning. This approach encourages students to design, conduct, and reflect on experiments relevant to the lesson material. When these projects incorporate natural materials readily available in the local environment, learning becomes more contextual, environmentally friendly, and meaningful (Miterianifa et al., 2021). For instance, purple cabbage extract can be used as a natural acid–base indicator, or common kitchen ingredients can be applied to investigate factors affecting reaction rates.

Acid–base chemistry is one of the most important topics in chemistry, with strong relevance to human life. This topic addresses the acidity of various solutions, including those widely used in daily activities (Riyayanti, 2021). Commonly used materials include litmus paper and commercially manufactured indicators to determine the acidity level of a solution (Novinta & Partana, 2021). Acid–base indicators are substances that undergo a color change depending on whether the solution is acidic or basic. In typical laboratory experiments, these indicators are used in liquid form, such as methyl red and phenolphthalein, or in paper form, such as pH indicator strips (Yadigaroglu et al., 2021). Many natural materials in the surrounding environment can also serve as acid–base indicators (Octaviani et al., 2023). Purple

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cabbage, for example, owes its characteristic color to anthocyanin pigments, which can be extracted to produce a blue–purple solution. Anthocyanins are highly sensitive to pH changes, displaying different colors under acidic, neutral, and basic conditions (Suhartati et al., 2021).

In addition to acid–base chemistry, the reaction rate is another topic well suited for natural material–based laboratory projects. Reaction rate refers to the speed at which reactant concentration decreases or product concentration increases over a specific period. This rate can be measured by monitoring either the reduction in reactant concentration or the increase in product concentration (Emmert et al., 2020). While concentration is generally expressed in moles per liter, gaseous reactions may also use pressure units such as atmospheres, millimeters of mercury, or pascals. Both topics, acid–base chemistry and reaction rate, are conceptually significant and closely related to everyday phenomena (Adella & Dalimunthe, 2024; Fantiani et al., 2023). For example, reaction rate experiments can utilize familiar household materials like eggshell waste and vinegar. Various factors affecting the reaction rate, such as temperature, surface area, and concentration, can be investigated (Wihardjo et al., 2024). Observations of carbon dioxide gas formation can be made using balloons to capture the gas. Through self-directed or collaborative experimental activities, students can simultaneously strengthen their critical thinking and scientific literacy skills.

Despite the potential of such activities, conventional chemistry education often remains theoretical, providing limited opportunities for optimal competency development. Traditional approaches tend to make students passive and restrict their ability to explore concepts in depth. While previous studies have examined different learning models, there is still a lack of research on the combined effects of project-based chemistry laboratories that employ environmentally friendly, natural materials to enhance scientific literacy and critical thinking skills.

The present study addressed this gap by proposing and examining an alternative model integrating natural materials into contextual, meaningful learning experiences. It adopted an active, student-centered, laboratory-based project learning approach, focusing on Grade XI senior high school students. The research employed a quasi-experimental design, with an experimental group conducting laboratory projects using natural indicators (e.g., purple cabbage extract), eggshell waste, and vinegar, while a control group received conventional instruction. These projects were intended to help students apply scientific concepts, critically analyze problems, and connect lessons to real-life contexts.

Method

This study employed a quasi-experimental design involving two classes selected through purposive sampling: an experimental group and a control group. Each group consisted of 15 Grade XI students from SMAN 12 Banjarmasin. The experimental group received instruction through project-based learning using natural materials, while the control group received conventional instruction.

Data were collected using post-test assessments to measure students' scientific literacy and critical thinking skills. The validity and reliability of the instruments were ensured through rigorous procedures. Content validity was established through expert judgment to verify alignment with the learning objectives. Reliability was confirmed using Cronbach's alpha coefficient, with a resulting value greater than 0.6, indicating an acceptable level of internal consistency.

The project-based learning intervention was implemented over two sessions. During this period, the experimental group engaged in collaborative laboratory projects, while the control group followed a standard lecture-based curriculum.

The research design applied was a non-equivalent post-test only control group design, in which two groups were compared:

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the experimental group and the control group. The design is illustrated in Table 1.

Table 1.
Non-Equivalent Post-Test Only Control Group Design

Class	Treatment	Post-test
Experiment	X	O1
Control	-	O2

Description:
X : Treatment
O1 : Post-test after treatment
O2 : Post-test of the control group

In this design, the experimental group received a treatment in the form of natural material-based chemistry laboratory projects while the control group did not. Upon completion of the learning process, both groups were administered a post-test to measure their scientific literacy and critical thinking skills (Yuniari et al., 2019).

Data analysis techniques included a normality test using the Kolmogorov–Smirnov method and a homogeneity test conducted using SPSS 25 software. If the data were found to be normally distributed and homogeneous, an independent samples t-test was performed to determine statistical differences between the groups.

Result and Discussion

Acceptable research instruments that meet academic standards are those that have undergone validity and reliability testing. Several factors affect the validity and reliability of data, including the quality of the data collection instrument and the object of measurement for a given research variable. The quality of a research instrument is determined primarily by its validity and reliability. The results of the validity test for the critical thinking instrument are presented in Table 2.

Table 2.
Validity Scores of Critical Thinking Instruments

Variable	Calculated *r*	Critical *r*	Sig.	Description
X1.1	0.904	0.3494	0.000	Valid
X1.2	0.835	0.3494	0.000	Valid
X1.3	0.693	0.3494	0.000	Valid
X1.4	0.835	0.3494	0.000	Valid

Based on the results in Table 2, the calculated r values were greater than the critical r value. In addition, the significance values were less than 0.005; therefore, items 1 to 4 were declared valid. The validity test results for the scientific literacy instrument are shown in Table 3.

Table 3.
Validity Scores of Scientific Literacy Instruments

Variable	Calculated *r*	Critical *r*	Sig.	Description
X2.1	0.980	0.3494	0.000	Valid
X2.2	0.980	0.3494	0.000	Valid
X2.3	0.980	0.3494	0.000	Valid
X2.4	0.980	0.3494	0.000	Valid
X2.5	0.758	0.3494	0.000	Valid

As shown in Table 3, all calculated r values exceeded the critical r value, and the significance values were below 0.005. Therefore, items 1 to 5 were declared valid.

After confirming instrument validity, the next step was to test reliability. Reliability refers to the extent to which a measuring instrument can be trusted or relied upon. If a measuring instrument, when used multiple times to assess the same phenomenon, produces relatively consistent results, it is considered reliable. In other words, reliability indicates the consistency of a measuring instrument in measuring the same phenomenon. The reliability test results for the critical thinking instrument are presented in Table 4.

Table 4.
Reliability of Critical Thinking Instruments

Cronbach's Alpha	*n* of Items
0.817	4

Based on the Cronbach's alpha value in Table 4, which exceeded 0.6, the critical thinking instrument was categorized as reliable. Similarly, the reliability test for the scientific literacy instrument is shown in Table 5.

Table 5.
Reliability of Scientific Literacy Instruments

Cronbach's Alpha	*n* of Items
0.957	5

As indicated in Table 5, the Cronbach's alpha value was greater than 0.6, demonstrating that the scientific literacy instrument was also categorized as reliable. According to PISA, scientific literacy is the ability to apply scientific knowledge to identify problems, draw evidence-based conclusions, and understand how human activities affect nature. It also encompasses an understanding of science as a product of discovery, awareness of the importance of science and technology for intellectual, environmental, and cultural development, and active participation in science-related issues (Vashti et al., 2020). Scientific literacy is not limited to mastering concepts and processes; it also guides individuals in making decisions and solving everyday problems based on scientific understanding (Pan et al., 2021). Individuals with scientific literacy can address problems using scientific concepts acquired through education and technology (Hatimah & Khery, 2021).

Dewi and Rahayu (2022) outline the following framework for levels of chemistry literacy: a) Scientific illiteracy: Students cannot relate to or respond to relevant scientific questions due to a lack of vocabulary, concepts, context, or cognitive skills needed to recognize them; b) Nominal scientific literacy: Students are familiar with science-related terms but cannot provide meaningful explanations. They can recall concepts or terms but lack genuine understanding and may hold misconceptions; c) Functional scientific literacy: Students can accurately define concepts based on their understanding, although their comprehension remains limited. This corresponds to the knowledge level (C2) in Bloom's taxonomy; d) Conceptual scientific literacy: Students have an in-depth understanding of scientific concepts, their interrelationships, scientific reasoning patterns, procedural skills, and the scientific inquiry process. They can further organize and integrate information rather than merely memorizing facts; e)

Multidimensional scientific literacy: Students demonstrate a broad understanding of science and technology from philosophical and historical perspectives, and can relate them to real-world and societal contexts. They connect interdisciplinary knowledge and recognize the interplay between science, technology, and complex social issues. This is considered the "true" form of scientific literacy.

The results of the scientific literacy tests for the control and experimental classes were then analyzed using SPSS version 25. The Shapiro–Wilk normality test results are presented in Table 6.

Table 6.
Normality Test of Science Literacy

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Control	.195	15	.128	.939	15	.366
Experiment	.156	15	.200*	.951	15	.540

**. This is a lower bound of the true significance.*
a. Lilliefors Significance Correction.

From the output in Table 6, the significance value for the experimental group was 0.540, and for the control group was 0.366. Since the significance values for both groups were greater than 0.05, and based on the decision criteria for the Shapiro–Wilk normality test, it could be concluded that the pre-test data on student learning outcomes for both the experimental and control groups were normally distributed. Following the normality test, a homogeneity test was conducted to determine whether the variances in the data were equal (homogeneous). The results are presented in Table 7.

Table 7.
Homogeneity Test of Science Literacy

		Levene Statistic	df1	df2	Sig.
Results	Based on Mean	.760	1	28	.391
	Based on Median	.774	1	28	.386
	Based on Median and adjusted df	.774	1	25.549	.387
	Based on trimmed mean	.684	1	28	.415

As shown in Table 7, the significance value based on the mean for the learning outcomes variable was 0.391. Since this value is greater than 0.05, it can be concluded that the variances of the post-test outcome data for the experimental and control groups were homogeneous.

To test the hypothesis, an independent samples t-test was conducted to determine whether there was a difference in the mean scores between the two groups. The learning outcomes of the control and experimental classes were analyzed using the t-test procedure, and the results are presented in Table 8.

As indicated in Table 8, the Sig. (2-tailed) value was 0.000, less than 0.05. Based on the decision criteria for the independent samples t-test, it can be concluded that there was a statistically significant difference between the science literacy scores of the control and experimental classes.

Table 8.
Independent Samples t-Test of Science Literacy

		Levene's Test for Equality of Variances		t-Test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Science literacy results	Equal variances assumed	.760	.391	-16.777	28	.000	-45.33333	2.70214	-50.86843	-39.79824
	Equal variances not assumed			-16.777	27.998	.000	-45.33333	2.70214	-50.86845	-39.79822

These findings suggest that project-based chemistry labs using natural materials provided authentic, real-world opportunities for students to develop cognitive flexibility while simultaneously strengthening their understanding of scientific concepts and literacy. This points to the potential of designing integrated learning environments prioritizing cognitive flexibility as an essential skill for effective problem-solving in science- and literacy-based contexts. These results align with those reported by Badaruddin et al. (2024), Sobach et al. (2023), and Thomas and Drew (2022).

The essence of critical thinking lies in cognitive abilities encompassing six core components: interpretation, analysis, evaluation, inference, explanation, and self-regulation (Anggraeni et al., 2024; Setianingsih et al., 2022). 1) Interpretation: the ability to understand and explain the meaning of experiences, data, situations, events, decisions, conversations, beliefs, rules, procedures, or specific criteria; 2) Analysis: the ability to identify intent and draw appropriate conclusions from statements, questions, concepts, or descriptions based on beliefs, observations, arguments, or other information; 3) Evaluation: the capacity to assess the credibility of information or statements, whether based on perceptions, experiences, beliefs, or logical reasoning, by examining the relevant inferential relationships between these elements; 4) Inference: the ability to determine and select the information needed to draw logical conclusions, form hypotheses, and predict outcomes from data, principles, opinions, or other relevant information; 5) Explanation: the ability to present the results of one's thinking clearly, justify reasoning based on evidence, methods, concepts, or criteria, and construct logical and convincing arguments; and 6) Self-regulation: awareness in monitoring and evaluating one's thought processes, including the elements used and the conclusions reached, by applying skills such as questioning, verifying, validating, and revising conclusions (Musahal et al., 2024; Ramirez & Paderna, 2024).

The critical thinking results for the control and experimental classes were then analyzed using SPSS version 25. The Shapiro–Wilk normality test results are shown in Table 9. A homogeneity test was conducted following the normality test to determine whether the data exhibited equal variances (i.e., homogeneity). The results are presented in Table 10.

As shown in Table 10, the significance value based on the mean for the learning outcomes variable was 0.594. Since this value is greater than 0.05, it can be concluded that the variances of the post-test results for the experimental and control groups were homogeneous.

Table 9.
Normality Test of Critical Thinking

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Experiment	.217	15	.055	.884	15	.054
Control	.142	15	.200*	.951	15	.539

**. This is a lower bound of the true significance.*
a. Lilliefors Significance Correction.

Table 10.
Homogeneity Test of Critical Thinking

		Levene Statistic	df1	df2	Sig.
Results	Based on Mean	.291	1	28	.594
	Based on Median	.237	1	28	.630
	Based on Median and adjusted df	.237	1	27.419	.630
	Based on trimmed mean	.254	1	28	.618

An independent samples t-test was then performed to evaluate the study's hypothesis. This test compared the mean scores between the control and experimental groups. The results are summarized in Table 11.

Table 11.
Independent Samples t-Test of Critical Thinking

		Levene's Test for Equality of Variances		t-Test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Results	Equal variances assumed	.291	.594	-13.742	28	.000	-39.533	2.877	-45.426	-33.641
	Equal variances not assumed			-13.742	26.342	.000	-39.533	2.877	-45.443	-33.624

As presented in Table 11, the Sig. (2-tailed) value was 0.000, which is less than 0.05. Based on the independent samples t-test decision rule, it can be concluded that there was a statistically significant difference in critical thinking scores between the control and experimental classes.

Students generally expressed a positive perception of project-based chemistry labs that incorporated natural materials. This positive view extended across several key areas, including the overall learning experience, the enhancement of critical thinking skills, and increased engagement with the subject matter.

The findings suggest that when students are given opportunities to explore chemical concepts through hands-on projects using everyday natural materials, their educational experience is significantly enriched. They reported higher levels of interest and involvement and perceived greater development in their ability to analyze, evaluate, and solve problems, which are essential skills for scientific inquiry. This indicates that integrating natural materials into a project-based laboratory format can foster a more engaging and impactful learning environment for chemistry students. These results align with those of Elfeky et al. (2025), Sutaryani et al. (2024), and Ospankulova et al. (2025).

Critical thinking is an essential competency in chemistry for students and professionals (Ananda et al., 2023). Its importance can be outlined as follows: 1) Understanding complex concepts: Chemistry requires more than memorization, as it involves grasping intricate concepts such as molecular structures, reaction mechanisms, and thermodynamics. In addition, critical thinking enables learners to comprehend the underlying "why" and "how" of chemical phenomena (Reynders et al., 2020); 2) Analyzing and interpreting data: Chemistry frequently involves processing experimental data, graphs, and observations. Critical thinking allows individuals to identify patterns, filter relevant from irrelevant information, detect inconsistencies, and draw logical conclusions (Sumarni & Kadarwati, 2020); 3) Constructing and evaluating arguments: Effective scientific practice involves building arguments grounded in evidence and logical reasoning, as well as evaluating the validity of others' arguments by identifying their strengths and weaknesses (Wale & Bishaw, 2020); and 4) Developing new solutions: From creating new pharmaceuticals to engineering sustainable materials, chemical innovation depends on creative and critical thinking to devise novel solutions to complex challenges (Kuhn, 2019).

From a reflective perspective, this research highlights the transformative potential of shifting from purely theoretical instruction toward more hands-on, relevant, and environmentally conscious teaching methods in chemistry. It reinforces the importance of critical thinking and scientific literacy as foundational skills for academic achievement and developing individuals capable of addressing real-world problems. The integration of natural materials makes learning more accessible and relatable while fostering sustainability awareness, an increasingly vital component of modern education. This study underscores that effective learning environments are active, contextual, and student-centred, encouraging deeper understanding and practical application of knowledge.

Conclusion

The implementation of project-based chemistry laboratory learning using natural materials, such as purple cabbage extract, eggshell waste, and a vinegar experiment, was proven effective in enhancing students' scientific literacy and critical thinking skills. Students in the experimental group, who participated in contextual and hands-on experiments on acid–base and reaction rate topics, demonstrated improved performance compared to those in conventional classes. This approach not only made learning more meaningful and environmentally friendly but also promoted deeper understanding and higher-order thinking skills. These findings underscore the potential of integrating natural resources into practical chemistry education as a novel and impactful pedagogical strategy. Future research could further examine its application across various topics and diverse student populations.

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