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Scaffolded stem-based project-based learning through sustainable fermentation product design to enhance creative thinking skills and environmental literacy

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Abstract. Creative thinking and environmental literacy are critical competencies for prospective biology teachers in addressing the demands of 21st-century education and the growing challenges of environmental sustainability. However, opportunities to develop these competencies through authentic learning experiences remain limited, particularly because learning and laboratory activities are still predominantly oriented toward a cookbook approach. This study investigated improvements in students' creative thinking skills and environmental literacy through the implementation of Scaffolded Project-Based Learning (PjBL) integrated with STEM through sustainable fermentation product design. A mixed-methods approach was employed. Quantitative data were collected through pretests and posttests involving 19 students and analyzed using descriptive statistics, paired-samples *t*-tests, N-Gain, and effect size. Qualitative data were obtained through worksheet analysis, interviews, observations, and documentation of project activities. The results showed that creative thinking skills increased from a mean score of 2.391 to 3.023, with an N-Gain of 0.393 (moderate category), indicating a statistically significant difference between pretest and posttest scores (t = -11.125, p < 0.001) and a very large effect size (Cohen's d = -2.552). Environmental literacy increased from 2.540 to 2.961, with an N-Gain of 0.288 (low category). At the same time, the difference between pretest and posttest scores was statistically significant (t = −5.333, p < 0.001), with a large effect size (Cohen's d = 1.224). Qualitative findings further indicated that students engaged in idea generation and decision-making, evidence-based problem solving, the use of locally available materials, and consideration of sustainability and waste reduction. The scaffolding progressively supported students in moving from reliance on instructional guidance toward greater autonomy in problem solving. Overall, STEM-integrated Scaffolded PjBL through sustainable fermentation product design shows promise as an authentic learning approach for fostering creative thinking and supporting environmental literacy among prospective biology teachers.
Keywords: Creative thinking skills, Environmental literacy, Scaffolded Project-Based Learning, STEM, Sustainable fermentation

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INTRODUCTION

In the 21st century, higher education is expected to prepare graduates who possess not only strong conceptual knowledge but also the creativity, innovativeness, adaptability, and problem-solving skills needed to address real-world challenges (Bridgstock, 2017). In line with the implementation of the Sustainable Development Goals (SDGs) and Education for Sustainable Development (ESD), higher education should integrate knowledge, skills, and sustainability values into learning to equip students with the capacity to develop solutions to pressing environmental and food-related challenges (Albareda-Tiana et al., 2018; Manzoor et al., 2024).

Food Microbiology courses have considerable potential to develop these competencies; however, their implementation is still predominantly characterized by theoretical instruction and verification-oriented laboratory activities. Students generally follow predetermined procedures in laboratory manuals, placing greater emphasis on confirming established concepts than on exploration and innovation (Brownell et al., 2012). Observations conducted at UIN

Raden Mas Said Surakarta indicated that students were not yet accustomed to designing fermentation products, evaluating alternative processing approaches, or considering sustainability aspects, such as the use of locally available raw materials, process efficiency, and waste reduction. This condition may constrain the development of students' creative thinking skills and environmental literacy.

Creative thinking skills and environmental literacy are complementary competencies that are essential for addressing the challenges of sustainable development. Creative thinking enables students to generate novel ideas, develop alternative solutions, modify fermentation processes and products (Birgili, 2015) and create food innovations that offer added value and respond to societal needs (Fatmawati, 2024). Meanwhile, environmental literacy equips students with the ability to understand the interrelationships between human activities and their environmental impacts (Fang et al., 2023) including the management of fermentation waste, sustainable utilization of local raw materials, waste reduction through the principles of *reduce, reuse,* and *recycle*, and the application of circular economy principles in food product development (Koban et al., 2026). Integrating these two competencies is increasingly important because food innovation is expected not only to meet quality and safety requirements but also to address environmental sustainability considerations (Bigliardi & Filippelli, 2022; León-Bravo et al., 2019; Lisboa et al., 2024). Therefore, Food Microbiology learning should be designed to provide learning experiences that foster students' creative thinking while simultaneously strengthening their environmental literacy, enabling them to develop innovative solutions that are ecologically responsible and contribute to the sustainability of food systems.

To address these challenges, a learning model is needed that integrates authentic learning experiences, multidisciplinary conceptual understanding, and learning support tailored to students' needs. Project-Based Learning (PjBL) provides opportunities for students to construct knowledge through the completion of authentic projects relevant to real-life contexts, thereby promoting active engagement, collaboration, and the development of innovative solutions (Bell, 2010). The effectiveness of PjBL can be further enhanced through integration with the Science, Technology, Engineering, and Mathematics (STEM) approach, which brings together scientific concepts, technology use, engineering design processes, and mathematical analysis to address complex problems (Jauhariyyah et al., 2017; Morgan et al., 2013). Through this integration, students are expected not only to understand food microbiology concepts but also to design, test, evaluate, and refine fermentation products based on scientific evidence. However, the complexity of project design can pose considerable challenges for students (Egelund et al., 2026) particularly when they are required to integrate concepts across disciplines and make informed decisions throughout the product development process. Accordingly, scaffolding becomes an important component for providing gradual and adaptive learning support through structured worksheets (Masruri et al., 2026), guiding questions, and continuous feedback aligned with students' developing competencies (Larkin, 2001).

Integrating PjBL, the STEM approach, and scaffolding is expected to create a more structured learning environment that encourages idea exploration and supports the development of students' creative thinking skills and environmental literacy. Integrating PjBL, the STEM approach, and scaffolding is expected to create a more structured learning environment that encourages idea exploration and supports the development of students' creative thinking skills and environmental literacy. Creative thinking skills enable students to generate innovative ideas and solutions, while environmental literacy supports their ability to understand environmental impacts and make responsible decisions. In sustainable food fermentation, these competencies are essential for designing innovative products while considering resource efficiency, waste reduction, and environmental sustainability.

Previous studies have shown that scaffolding within STEM/STEAM-based Project-Based Learning (PjBL) can enhance learning quality. Fuster-barceló et al. (2023) demonstrated that scaffolding can effectively support interdisciplinary collaboration and the resolution of authentic problems. Ruangurai et al. (2022) reported that scaffolding helped students develop an understanding of abstract concepts through project-based activities, thereby enhancing engagement and systematic thinking. Similarly, Yanti et al. (2023) found that the Multiple Scaffolding STEAM-PjBL model significantly improved students' learning outcomes, critical thinking skills, and learning motivation.

Despite these findings, existing studies have primarily focused on outcomes such as interdisciplinary collaboration, systematic thinking, critical thinking, and learning motivation. Comparatively little attention has been given to integrating Scaffolded Project-Based Learning within a STEM framework and the context of sustainable fermentation product design to simultaneously foster creative thinking skills and environmental literacy as key competencies for Education for Sustainable Development (ESD). To address this gap, the present study introduces a Scaffolded Project-Based Learning approach integrated with STEM through sustainable fermentation product design, with scaffolding embedded throughout the project stages. This approach engages students in generating creative solutions to authentic problems while strengthening their environmental literacy by applying sustainability principles.

METHOD

Research design

This study employed a mixed-methods approach with an embedded mixed-methods design, in which quantitative data served as the primary source of evidence. Qualitative data were used as supplementary data to corroborate and further explain the quantitative findings. The study adopted a pre-experimental design using a One-Group Pretest–Posttest Design (Cohen et al., 2018). In this design, students completed a pretest before the intervention and a posttest after instruction using STEM-integrated Scaffolded Project-Based Learning through sustainable fermentation product design. Differences between the pretest and posttest scores were analyzed to examine changes in students' creative thinking skills and environmental literacy following the learning intervention.

Research participants

The study included fourth-semester students enrolled in the Biology Education (Tadris Biologi) program who were taking a Microbiology course. A total of 20 students participated in the study and were selected using a total sampling technique, whereby all students enrolled in the course were included as research participants. Participants were selected based on their alignment with the study objectives, particularly the development of creative thinking skills and environmental literacy through project-based learning in the Microbiology course.

Research instrument

The research instruments comprised quantitative and qualitative instruments. The quantitative instruments included a creative thinking skills test and an environmental literacy questionnaire. The creative thinking skills test was developed based on the dimensions of creative thinking proposed by Greenstein (2012), including curiosity, fluency, originality, elaboration, flexibility, divergent thinking, risk-taking/messiness, and collaboration/with others. The environmental literacy questionnaire was developed based on four dimensions of environmental literacy: (1) knowledge and understanding of environmental concepts, problems, and issues; (2) cognitive and affective dispositions, including attitudes, values, concern, and responsibility toward the environment; (3) competencies or skills, encompassing thinking and cognitive skills for analyzing and solving environmental problems; and (4) behavioral strategies, referring to the ability to apply environmental knowledge and skills in real-world actions and make effective decisions across different environmental contexts (Hollweg et al., 2011). The qualitative instruments included a learning implementation observation sheet, analyses of students' worksheets, documentation of the project processes and products, and a semi-structured interview protocol. These instruments were used to obtain in-depth information about students' learning experiences throughout the implementation of the learning intervention.

Data collection techniques

Quantitative data were collected through pretests and posttests to assess changes in students' creative thinking skills and environmental literacy before and after the learning intervention. Qualitative data were collected through observations conducted throughout the learning process, documentation of students' project activities and products, and semi-structured interviews with purposively selected students. The qualitative data provided in-depth insights into students' learning experiences, challenges encountered during the project, and perceived benefits of the learning intervention.

Instrument validity and reliability testing

Before administration, experts in Food Microbiology and Biology Education reviewed the research instruments to assess content validity, construct validity, and linguistic clarity. Empirical validity was subsequently examined using Pearson's product-moment correlation, while instrument reliability was assessed using Cronbach's alpha. With $N = 20$ and a 5% significance level ($df = 18$), the critical correlation value was (r_{table}=0,444).

The results indicated that all eight items measuring creative thinking skills were empirically valid, with $r_{calculated}$ values ranging from 0.668 to 0.872, and all items showed $p <$ 0.05. The instrument demonstrated excellent internal consistency, with a Cronbach's alpha coefficient of 0.896.

For the environmental literacy instrument, all four items were also valid, with $r_{calculated}$ values ranging from 0.614 to 0.849 and $p < 0.05$. The instrument demonstrated good internal consistency, with a Cronbach's alpha coefficient of 0.724. Overall, both instruments demonstrated adequate empirical validity and reliability and were therefore considered suitable for use in the study.

Data analysis techniques

Data were analyzed using both quantitative and qualitative approaches. Quantitative data were analyzed descriptively to obtain the mean, standard deviation, and percentage increase. Prior to hypothesis testing, assumption tests were conducted, including the Shapiro–Wilk test for normality and Levene's test for homogeneity of variance. The normality test indicated that the environmental literacy data were normally distributed ($W = 0.920$, $p = 0.111 > 0.05$), as were the creative thinking skills data ($W = 0.957$, $p = 0.506 > 0.05$). Levene's test indicated homogeneous variances for both environmental literacy (Levene's statistic = 0.168, $p = 0.684 > 0.05$) and creative thinking skills (Levene's statistic = 0.193, $p = 0.663 > 0.05$).

Based on these assumption tests, the data satisfied the normality and homogeneity assumptions required for parametric analysis. Differences between pretest and posttest scores were examined using paired-samples *t*-tests. The magnitude of improvement was assessed using the normalized gain (N-Gain), while the magnitude of the intervention effect was evaluated using Cohen's *d*. The N-Gain values were interpreted using three categories: low ($g < 0.30$), medium ($0.30 \leq g < 0.70$), and high ($g \geq 0.70$) (Hake, 1998). Qualitative data were analyzed through data reduction, data display, and conclusion drawing, followed by triangulation with the quantitative findings. This integration provided a more comprehensive interpretation of the learning intervention's effectiveness.

Learning intervention

Framework of scaffolded STEM project-based learning

The learning intervention employed a Scaffolded Project-Based Learning (SPjBL) approach integrated with the Engineering Design Process (EDP) adapted from Morgan et al. (2013). The intervention engaged students in solving authentic problems by designing and developing sustainable fermentation products while integrating the four STEM disciplines. Throughout the learning process, scaffolding was embedded to provide cognitive, metacognitive, and procedural support, with assistance gradually reduced (*fading scaffolding*) as students became more independent in completing the project (Morgan et al., 2013).

The learning framework consisted of ten sequential phases: (1) identifying the problem, (2) defining the problem, (3) generating alternative solutions, (4) analyzing constraints, (5) researching information, (6) developing the best solution, (7) selecting the optimal solution, (8) planning the STEM project, (9) developing the STEM product, and (10) testing, refining, communicating, and reflecting on the project outcomes. Table 1 presents the detailed learning framework, corresponding EDP phases, and scaffolding strategies.

Learning implementation procedure

The intervention was conducted over 8 instructional sessions, with each session corresponding to one or more phases of the Scaffolded STEM-PjBL framework. At the beginning of the intervention, students were introduced to authentic environmental issues related to sustainable fermentation products. They observed contextual phenomena, identified problems, and formulated investigable questions that guided subsequent project activities.

During the problem-analysis phase, students generated multiple alternative solutions, identified the constraints associated with each alternative, and gathered scientific evidence from textbooks, scientific articles, laboratory observations, and digital resources. Based on the collected evidence, each group synthesized the information to formulate and select the most feasible solution considering scientific validity, technical feasibility, resource availability, and environmental sustainability.

In the project-planning phase, students prepared a project implementation plan, including experimental procedures, required materials, project schedules, and expected outcomes. Students then implemented the plan through collaborative project activities in which they developed sustainable fermentation products, documented experimental observations, collected data, and evaluated the effectiveness of their designs. The final phase involved testing the developed products using predetermined evaluation criteria, refining them based on the results, communicating project outcomes through group presentations, and reflecting on both the design process and learning experiences. Reflection activities encouraged students to evaluate their problem-solving strategies, scientific reasoning, creativity, and environmental responsibility developed throughout the project.

Scaffolding was systematically integrated throughout all learning phases. Cognitive scaffolding was provided through guiding questions, structured worksheets, conceptual prompts, and formative feedback to support conceptual understanding. Metacognitive scaffolding encouraged students to monitor, evaluate, and justify their decisions during problem-solving, whereas procedural scaffolding guided students in planning, conducting, and evaluating the project. As students demonstrated increasing competence, instructional support was progressively withdrawn (*fading scaffolding*), allowing greater learner autonomy in completing the project.

Table 1. Framework for implementing STEM-based scaffolded project-based learning

STEM-PjBL Syntax	Student Activities	Engineering Design Process (EDP)	Scaffolding Strategy
Identifying the Problem	Observe a contextual phenomenon related to sustainable fermentation, identify the problem, and recognize the needs and constraints that influence problem-solving.	Identify Problem and Constraints	The instructor presents an authentic phenomenon, provides guiding questions, and activates students' prior knowledge.
Defining the Problem	Formulate the problem as a clear, measurable, and solvable investigative question that can be addressed through a STEM project.	Identify Problem and Constraints	The instructor provides examples of problem formulation, structured worksheets, and initial feedback.
Generating Alternative Solutions	Develop multiple alternative solutions based on science, technology, engineering, and mathematics concepts.	Identify Problem and Constraints	Structured brainstorming, guiding questions, and collaborative discussions.
Analyzing Constraints	Analyze the constraints associated with each alternative in terms of technical feasibility, cost, time, safety, and environmental sustainability.	Identify Problem and Constraints	Constraint-analysis checklists, prompting, and metacognitive scaffolding to encourage consideration of multiple factors
Researching Information	Search for and evaluate relevant scientific information to support informed decision-making.	Identify Problem and Constraints	The instructor provides curated learning resources, investigative questions, and guidance in information literacy.
Developing the Best Solution	Synthesize information and design the most appropriate solution based on the identified needs and constraints.	Identify Problem and Constraints	Design templates, consultations, and formative feedback on the proposed solution.
Selecting the Optimal Solution	Evaluate alternative solutions through group discussions based on criteria of effectiveness, feasibility, and sustainability, and then select the solution to be developed.	Identify Problem and Constraints	Reflective questions, guided discussions, and instructor feedback to support decision-making
Planning the STEM Project	Develop an implementation plan, including work procedures, materials and equipment, a project timeline, and indicators of STEM product success.	Research & Ideate	Project-planning templates, coaching, and planning monitoring.
Developing the STEM Product	Develop and implement the sustainable fermentation product according to the design, and document the project processes and outcomes	Analyze Ideas & Build	Coaching during implementation, periodic monitoring, and formative feedback.
Testing, Refining, and Reflecting	Test product performance, analyze the results, refine the product, communicate the project outcomes, and reflect on the learning process.	Test and Refine; Communicate and Reflect	Assessment rubrics, peer feedback, guided reflection, and summative feedback.

RESULTS AND DISCUSSION

Creative thinking skills and environmental literacy are essential competencies for prospective biology teachers to meet the demands of 21st-century education. Beyond mastering biological concepts, prospective teachers are expected to generate creative ideas, develop innovative solutions to environmental challenges, and integrate environmental issues into their teaching practices. Developing these competencies is therefore essential to preparing adaptive, innovative biology teachers who are responsive to environmental sustainability. The following section presents findings from implementing STEM-integrated Scaffolded Project-Based Learning through Sustainable Fermentation Product Design. It discusses its contribution to developing prospective biology teachers' creative thinking skills and environmental literacy.

Environmental literacy

Environmental literacy refers to an individual's ability to understand environmental concepts and issues, demonstrate concern for the environment, and apply relevant knowledge to inform attitudes and actions that support environmental sustainability. In this study, environmental literacy was examined across four dimensions: knowledge, cognitive and affective dispositions, skills, and behavioral strategies. Table 2 presents changes in students' environmental literacy before and after implementing STEM-integrated Scaffolded Project-Based Learning through sustainable fermentation product design.

Table 2. Descriptive statistics and changes in students' environmental literacy

Variabel	N	Score Max	Pretest Mean ± SD	Posttest Mean ± SD	Mean Increase	N-Gain	Category
Environmental literacy	19	4.00	2.540 ± 0.393	2.961 ± 0.366	0.421	0.288	Low

Based on Table 2, students' environmental literacy increased after the learning intervention. The mean score increased from 2.540 ± 0.393 in the pretest to 2.961 ± 0.366 in the posttest, representing a mean increase of 0.421 points. The N-Gain value of 0.288 indicates that the improvement in environmental literacy was in the low category. The decrease in standard deviation from 0.393 to 0.366 also suggests that posttest scores were more homogeneous than pretest scores.

The relatively low N-Gain suggests that improvements in environmental literacy do not occur automatically as a result of students' participation in project-based learning. Environmental literacy is a multidimensional construct encompassing knowledge, cognitive and affective dispositions, skills, and behavioral strategies (Hollweg et al., 2011). PjBL can readily provide opportunities to develop knowledge and skills because students are directly engaged in investigation, data processing, and product development. However, changes in environmental concern, values, responsibility, and particularly behavioral strategies require deeper internalization and sustained learning experiences. Previous research has also indicated that project-based learning can enhance environmental literacy, although its effectiveness depends on the project's characteristics and the environmental context in which learning takes place (Nurfarida & Abidin, 2026).

The findings can also be attributed to the design of the projects implemented in this study. Analysis of the students' worksheets revealed that most of the project questions remained primarily focused on fermentation product quality, including the thickness and weight of nata, the pH and sensory characteristics of kombucha, the texture and aroma of yogurt/soyghurt, and the color, texture, aroma, and taste of tempeh. Although the project activities gave students opportunities to use local materials and develop fermentation products, environmental issues were not yet fully positioned as the *driving questions* guiding the entire investigation process. Consequently, the project experience may have provided greater opportunities to develop product-oriented knowledge and skills than to foster deeper environmental understanding and behavioral dispositions, which may explain why environmental literacy improvement remained in the low category. Table 3 shows the results of the environmental literacy t-test.

Table 3. Paired-samples *t*-test results for environmental literacy

Comparison	Mean Difference	SD	SE Mean	t	df	Sig. (2-tailed)
Pretest - posttest	-0.42105	0.34412	0.07895	-5.333	18	< 0.001

The paired-samples *t*-test results presented in Table 3 revealed a statistically significant difference in students' environmental literacy scores following the implementation of STEM-integrated *Scaffolded Project-Based Learning* ($t(18) = -5.333$, $p < 0.001$). The mean score increased by 0.421 points, from 2.5395 in the pretest to 2.9605 in the posttest. This finding suggests that students' engagement in the fermentation projects was associated with improved understanding of and responsiveness to environmental issues.

The significant pretest-posttest difference indicates that the STEM-integrated PjBL experience engaged students in more than the passive acquisition of information about fermentation and environmental issues. Throughout the project, students identified problems, sought relevant information, evaluated alternatives, designed products, tested outcomes, and reflected on the results. These interconnected activities gave students opportunities to connect disciplinary concepts with authentic problems, making environmental knowledge more contextualized and meaningful.

Scaffolding also played an important role in structuring students' learning processes. Guiding questions, constraint analysis, information searching, solution selection, product testing, and reflection supported students in understanding problems and making decisions progressively. This finding is consistent with Holton & Clarke (2006), who emphasized that scaffolding can support the development of metacognitive processes and gradually enable learners to assume greater control over their learning. Gunawardena & Wilson (2021) reported that scaffolding can support the development of critical thinking, while Alanazi (2024) found that scaffolding strategies can enhance higher-order thinking in science learning. Collectively, these findings support the interpretation that scaffolding within STEM-integrated PjBL can help students transform project-based experiences into a more meaningful understanding of environmental issues. Table 4 shows the results of the environmental literacy effect size test.

Table 4. Effect sizes for the pretest–posttest difference in environmental literacy

Variable	Comparison	Effect Size Type	Standardizer	Effect Size Value	95% CI (Lower)	95% CI (Upper)
Environ-mental literacy	Pretest – Posttest	Cohen's d	0.34412	-1.224	-1.814	-0.614
		Hedges' g	0.35151	-1.198	-1.775	-0.601

Based on Table 4, the effect size analysis indicates a large improvement in environmental literacy. Cohen's *d* was -1.224, with a 95% confidence interval (CI) of -1.814 to -0.614, while Hedges' *g* was -1.198, with a 95% CI of -1.775 to -0.601. The negative signs indicate the direction of the difference, with posttest scores being higher than pretest scores. Based on the absolute magnitude of the effect size ($d = 1.224$), the learning intervention had a large effect on improvements in students' environmental literacy. This finding further supports the paired-samples t-test results, which showed a statistically significant difference between pretest and posttest scores ($p < 0.001$).

The large effect size observed in this study is consistent with previous research highlighting the value of Project-Based Learning (PjBL) in promoting active, experiential, and innovation-oriented learning. Omelianenko & Artyukhova (2024) explained that PjBL engages students in authentic problems through problem identification, research, project development, collaboration, and reflection. Similarly, the sustainable fermentation projects in this study involved students in selecting materials, designing and testing products, evaluating results, and improving their solutions. During these activities, students considered local and underutilized materials, resource efficiency, and potential waste. These experiences helped students connect microbiological concepts with environmental issues and real-world sustainability challenges.

These findings are also consistent with Baran et al., (2021) who found that PjBL-STEM activities using waste materials improved students' 21st-century skills, including environmental sensitivity, autonomy, cooperation, problem solving, creativity, critical thinking, and environmental awareness. Although the study focused on 21st-century skills rather than environmental literacy as a multidimensional construct, it supports using environmentally oriented PjBL-STEM to develop students' awareness of and responses to environmental issues. In the present study, using local and underutilized materials in sustainable fermentation projects provided a similar environmental context. However, this study extended the focus to environmental literacy by encouraging students to consider resource use, waste reduction, and sustainability during product development.

Scaffolding also played an important role in guiding students through the projects' complexity. Gradual support through guiding questions, constraint analysis, information searching, solution selection, product testing, and reflection helped students move beyond simply producing fermentation products to considering the environmental aspects of their decisions. This finding is consistent with Elder et al. (2023), who showed that *learning-by-doing* supported by scaffolding and mentoring can develop sustainability competencies and promote learner independence. Thus, scaffolding not only supported students during the project but also helped them connect their project experiences with broader sustainability issues.

The findings are further supported by Farida et al. (2017), who reported that PjBL integrating environmental themes can develop scientific skills and environmental literacy. Similarly, Klein et al. (2021) found that projects focusing on environmental issues and real-world actions can strengthen environmental literacy and encourage students to participate in problem-solving. A similar pattern was observed in this study, as all dimensions of environmental literacy increased, as shown in Figure 1. Overall, these findings suggest that authentic environmental contexts, when integrated into project activities and supported by STEM and scaffolding, can provide meaningful opportunities for students to develop environmental literacy.

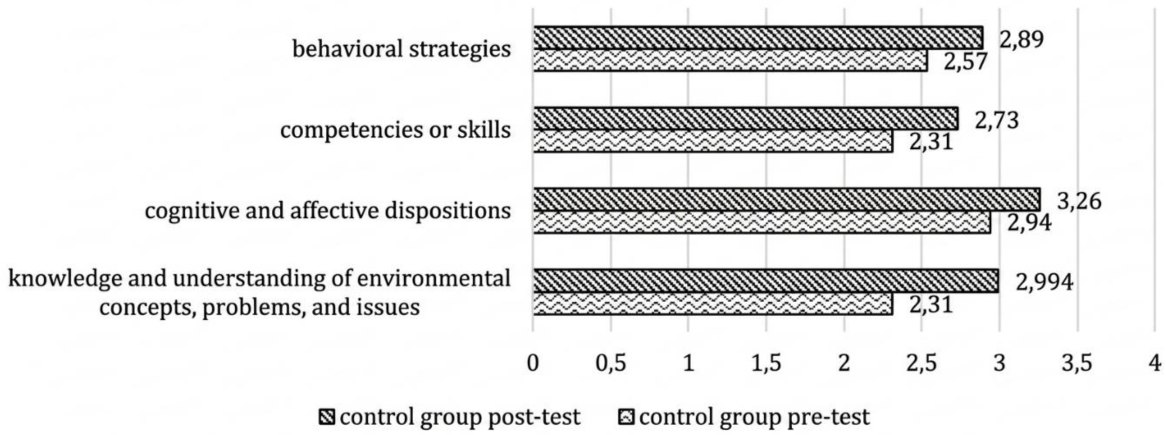

Figure 1. Environmental literacy by dimension (pretest-posttest)

As shown in Figure 1, all dimensions of environmental literacy increased from the pretest to the posttest. The highest posttest score was found for cognitive and affective dispositions (3.26), indicating that the learning activities helped foster students' environmental awareness, attitudes, and concern about environmental issues. In contrast, the lowest posttest score was observed for environmental skills (2.73), suggesting that students' ability to apply their knowledge to analyze and address environmental problems still requires further development.

The greatest improvement occurred in the knowledge dimension, which increased from 2.31 to 2.994. This finding suggests that the fermentation projects provided direct learning experiences that helped students understand environmental concepts and issues. In contrast, the smallest improvement was observed in behavioral strategies, which increased from 2.57 to 2.89. This pattern suggests that knowledge and attitudes may develop more readily through project-based learning, whereas translating environmental understanding into actual behavior requires sustained experience, opportunities for application, and repeated practice

These findings are consistent with Pertiwi et al. (2024), who reported that integrating STEM into PjBL can improve environmental literacy. Perrault & Albert (2018) similarly found that PjBL can improve students' attitudes toward sustainability. In addition, Ayoub Moubareck (2022) showed that PjBL in microbiology education can enhance not only students' knowledge but also encourage environmentally oriented practices, such as household composting. However, behavioral changes were not observed consistently across all students or all forms of environmental management. Therefore, the findings suggest that PjBL can effectively strengthen students' environmental knowledge and attitudes, whereas developing behavioral strategies requires sustained hands-on experiences, opportunities to apply knowledge in real contexts, and continuous practice.

Creative Thinking Skills

Creative thinking skills refer to an individual's ability to generate diverse ideas, develop alternative solutions, evaluate ideas, and produce novel solutions to address problems. In this study, creative thinking skills were developed through the design and development of sustainable fermentation products, which required students to identify problems, generate ideas, solve problems, and evaluate solutions. Table 5 presents changes in students' creative thinking skills before and after the learning intervention.

Table 5. Descriptive statistics of creative thinking

Variabel	N	Maximum Score	Pretest Mean ± SD	Posttest Mean ± SD	Mean Increase	N-Gain	Category
Creative thinking skills	19	4.00	2.391 ± 0.379	3.023 ± 0.237	0.633	0.393	Medium

As shown in Table 5, students' creative thinking skills improved after the learning intervention. The mean score increased from 2.391 ± 0.379 in the pretest to 3.023 ± 0.237 in the posttest, representing a mean increase of 0.633 points. The N-Gain value was 0.393, which falls within the medium category. The decrease in standard deviation from 0.379 to 0.237 also indicates that students' posttest scores were relatively more homogeneous than their pretest scores. Table 6 presents the t-test for creative thinking skills.

Table 6. Paired-samples *t*-test results for creative thinking skills

	Mean Difference	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
pretest - posttest	- 0.63263	0.24788	0.05687	-11.125	18	0.000

The paired-samples *t*-test results in Table 6 show a statistically significant difference in students' creative thinking skills before and after the learning intervention. The mean difference between the pretest and posttest scores was -0.63263, with $t(18) = -11.125$ and $p < 0.001$. Because the p-value was below 0.05, the null hypothesis was rejected, indicating a significant difference between students' pretest and posttest scores. The negative mean difference reflects the direction of change, indicating that students' posttest scores were higher than their pretest scores. These findings demonstrate that the learning intervention was associated with a significant improvement in students' creative thinking skills.

Students' mean creative thinking score increased from 2.391 to 3.023, representing an increase of 0.633 points (26.47%). This result indicates a significant improvement in students' creative thinking skills following the learning intervention. The increase suggests that students developed a greater capacity to generate and elaborate ideas through the learning activities. This finding is also consistent with the descriptive results, which showed an increase in the mean score and a decrease in the standard deviation from 0.379 to 0.237, indicating more consistent performance among students on the posttest. Table 7 presents the effect size for creative thinking skills.

Table 7. Effect sizes for the pretest–posttest difference in creative thinking skills

Variable	Comparison	Effect Size Type	Standardizer	Effect Size Value	95% CI (Lower)	95% CI (Upper)
Creative thinking skills	Pretest - Posttest	Cohen's d	0.24788	-2.552	-3.485	-1.603
		Hedges' g	0.25319	-2.499	-3.412	-1.569

As presented in Table 7, the effect size analysis revealed a substantial difference between students' pretest and posttest creative thinking skills. The analysis yielded a Cohen's *d* value of -2.552 and a Hedges' *g* value of -2.499, with 95% confidence intervals ranging from -3.485 to -1.603 and from -3.412 to -1.569, respectively. Based on the absolute values of the effect sizes, both Cohen's *d* and Hedges' *g* indicate a very large effect. The negative values reflect the direction of the comparison, as the difference was calculated by subtracting the posttest scores from the pretest scores. Thus, the results indicate that students' creative thinking skills improved substantially from the pretest to the posttest.

The large effect may be related to the characteristics of STEM-integrated PjBL, which provided students with opportunities to address problems and develop products. Rather than simply following predetermined procedures, students identified problems, generated alternatives, considered constraints, searched for information, selected solutions, designed products, tested them, and refined their designs. These activities provided opportunities to generate ideas, develop alternatives, modify designs, and find solutions. This finding is consistent with Kwon & Lee (2025), whose meta-analysis showed that STEM-PjBL has a large effect on creativity. Their findings support the present study by suggesting that integrating STEM into PjBL can create learning contexts that encourage students to generate and develop multiple solutions to problems.

Pratiwi et al. (2021) also found that PjBL integrated with STEM improved students' creativity, with the experimental group achieving a higher N-Gain than the control group. Similarly, Subekti et al. (2025) and Nurmaliah et al. (2021) reported that PjBL-STEM can improve problem-solving skills. These findings are relevant because problem-solving processes in PjBL-STEM provide students with opportunities to explore alternatives and select appropriate solutions, which are important components of creative thinking. Therefore, the activities of designing, testing, and refining fermentation products in the present study provided students with an authentic context for developing creativity through real-world problem-solving.

Beyond the characteristics of STEM-integrated PjBL, *scaffolding* may also have strengthened students' creativity. Guidance through prompting questions, problem analysis, information searching, and alternative evaluation helped students develop their ideas progressively without determining the solutions they had to choose. This finding is consistent with Maksić & Jošić (2021), who suggested that cognitive scaffolding can support the development of knowledge, critical thinking, and divergent thinking. Thus, *scaffolding* in the present study provided both direction and space for students to explore different possibilities, allowing the STEM-PjBL experience to support substantial gains in creative thinking skills. This development is further reflected in the improvement across the individual dimensions of creative thinking skills, as presented in Figure 2.

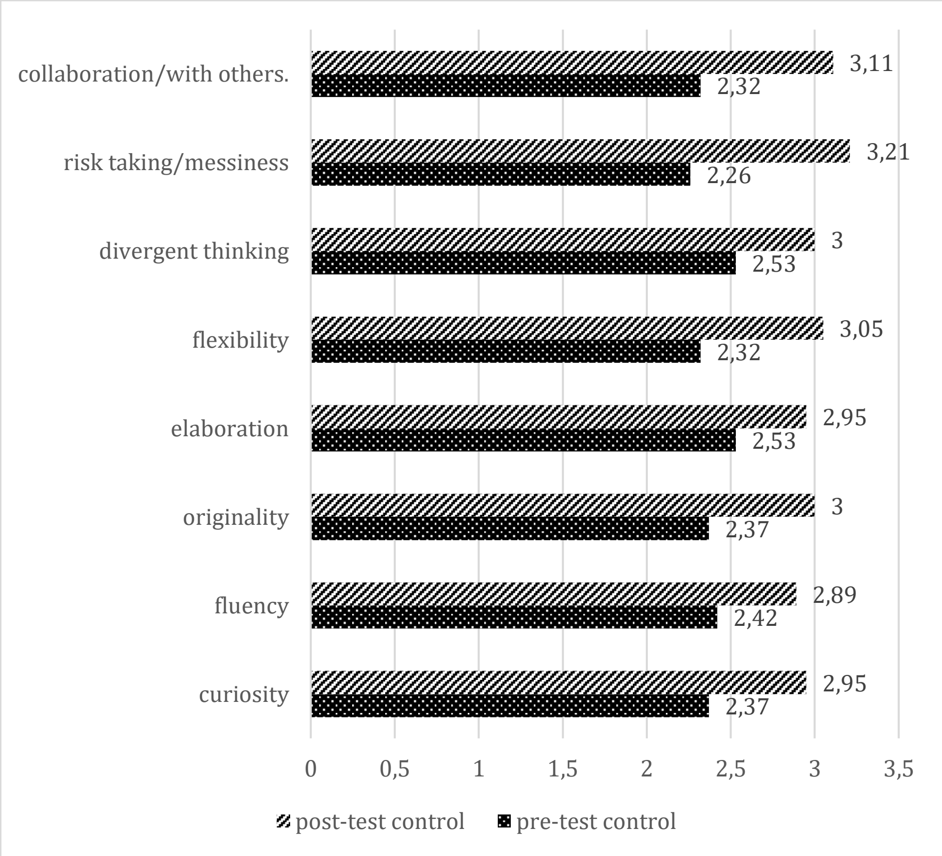

Figure 2. Pretest–posttest scores for each dimension of creative thinking skills

As shown in Figure 2, all dimensions of creative thinking skills increased from the pretest to the posttest. The highest posttest score was observed for Risk Taking/Messiness (3.21), whereas the lowest was found for Fluency (2.89). The greatest improvement occurred in Risk Taking/Messiness, increasing from 2.26 to 3.21 (0.95 points), while the smallest improvement was found in Elaboration, increasing from 2.53 to 2.95 (0.42 points). Improvements were also observed in Collaboration/With Others, Divergent Thinking, Flexibility, Originality, and Curiosity.

These findings are consistent with Sumarni & Kadarwati (2020), who reported that *ethno-STEM project-based learning* can improve various dimensions of creative thinking. Similarly, a meta-analysis by Feziyasti et al. (2025) showed that STEM-integrated PjBL has a large effect on creativity by engaging students in real-world problem-solving. Megawati (2024) also reported a positive trend for STEM-PjBL in higher education biology toward developing students' cognitive and practical skills. In addition, Indrasti & Paidi (2025) found that contextual problem-based PjBL-STEM can improve higher-order thinking skills. These findings support the present study by indicating that project activities involving authentic problems can provide students with opportunities to generate ideas and develop alternative solutions.

The worksheet analysis and interview findings further showed that students initially needed support in identifying problems and initiating product designs. The instructor provided guiding questions, directions, and gradual feedback without directly providing solutions. This support helped students explore alternatives, evaluate outcomes, and refine their products until they could make decisions more independently. Thus, the improvement in creativity may be attributed not only to the project activities but also to *scaffolding*, which provided support according to students' needs and gradually reduced assistance as their abilities developed. This is consistent with Smagorinsky (2018), who described scaffolding as support that enables learners to perform tasks they cannot yet complete independently and gradually develop greater autonomy in learning.

The project activities also showed that students actively explored materials, designed and developed products, and modified them during the fermentation process. These experiences provided an authentic context for developing creative thinking while also applying environmental considerations, particularly in the use of local resources, material efficiency, and potential waste reduction. Documentation of the project implementation is presented in Figure 3.

Figure 3. Documentation of students' fermentation product development activities: (a) K2, (b) K3, (c) K4, and (d) K1, showing the stages of material preparation, processing, formulation, and fermentation product development.

As shown in Figure 3, students were actively involved in various stages of fermentation product development, including material preparation and processing, formulation, mixing, and product observation. The variation in activities and materials used by each group indicates that students explored and implemented different product designs. Rather than simply following predetermined procedures, students were directly involved in experimentation and decision-making throughout the product development process. This documentation supports the worksheet and interview findings, indicating that the learning process provided authentic experiences involving product design, testing, observation, and evaluation. Table 8 presents the analysis of students' worksheets on the development of creative thinking skills and environmental literacy.

Table 8. Evidence of creative thinking and environmental literacy development based on students' worksheets

Group	Project	Evidence of Creative Thinking Development	Evidence of Environmental Literacy Development
K1	Nata produced from different fruit types.	Students compared several fruit types and predicted their effects on nata thickness, weight, and fiber content. They then evaluated the results and selected the fruit type that produced the best product. These activities provided evidence of curiosity, fluency, flexibility, divergent thinking, elaboration, and evaluation of alternatives.	Using different fruit types provided an opportunity to consider local and underutilized resources. However, the worksheet questions focused primarily on product quality (thickness, weight, and fiber content); therefore, the problem formulation did not explicitly incorporate environmental knowledge and sustainability considerations.
K2	Roselle–butterfly pea flower kombucha with different sugar concentrations	Students investigated three sugar concentrations (10%, 15%, and 20%), monitored pH changes, assessed sensory characteristics, compared alternatives, and selected the most appropriate formulation. These activities demonstrated curiosity, fluency, flexibility, divergent thinking, elaboration, and decision-making	The use of roselle and butterfly pea flowers provided a context for utilizing locally available biological resources. However, the research questions did not explicitly address resource efficiency, sugar use, waste generation, or environmental impacts.
K3	Yoghurt and soy yoghurt with different starter cultures.	Students compared different starter cultures and evaluated their effects on texture, viscosity, aroma, taste, and color. Comparing alternatives and evaluating product characteristics demonstrated fluency, flexibility, elaboration, divergent thinking, and evaluation of solutions.	Using soybean as a raw material in soyghurt provided a context for discussing resource utilization and alternative food materials. Nevertheless, the research questions did not explicitly address environmental impacts, resource efficiency, or waste management.
K4	Tempe supplemented with different spices.	Students explored several types of spices, compared their effects on color, texture, aroma, and taste, and selected the formulation producing the most desirable product. Investigating the effects of spices on the fermentation process also involved curiosity, flexibility, elaboration, divergent thinking, problem solving, and evaluation of solutions.	Using spices as supplementary materials created opportunities to explore local biological resources and material utilization. However, the problem formulation did not explicitly incorporate waste reduction, resource efficiency, or environmental impacts.

Based on Table 8, project activities across all groups provided evidence of developing creative thinking skills, particularly through exploring alternatives, comparing options, analyzing results, evaluating solutions, and making decisions. The most evident indicators were *curiosity, fluency, flexibility, divergent thinking,* and *elaboration*. In contrast, environmental literacy was developed more implicitly through the use of local materials and available resources. However, resource efficiency, waste reduction, and environmental impacts were not yet explicitly incorporated into most groups' research questions. These findings are consistent with the quantitative results, which showed a greater improvement in creative thinking, whereas the gain in environmental literacy remained in the low category.

The increase in students' creative thinking skills and environmental literacy is due to empowerment at every step of the PjBL-STEM learning model as follows.

Identifying the problem

At the *identifying the problem* stage, the lecturer provided scaffolding through guiding questions, problem examples, and observation prompts to help students identify authentic problems related to fermentation and environmental issues. This stage mainly supported *curiosity* and *divergent thinking*, as students were encouraged to observe phenomena, ask questions, and consider different perspectives. It also developed environmental knowledge and understanding and began to foster cognitive and affective dispositions, particularly awareness of resource use and potential waste.

Interview findings supported this development. Students began to recognize underutilized materials and food residues as potential resources rather than merely waste. M2 noted that *"underutilized materials or food residues can be processed into products with added value, so they do not immediately become waste,"* while M4 emphasized the use of local materials to reduce waste and optimize available resources. These findings indicate that authentic fermentation contexts helped students connect biological concepts with environmental issues. This is consistent with Pertiwi et al. (2024), who found that STEM-integrated PjBL can support environmental literacy, and Wahyudi et al. (2025)**,** who reported that PjBL-STEM integrated with *green chemistry* can develop both *creative thinking* and *environmental literacy*. Thus, problem identification served as an important starting point for connecting project experiences with the development of these two competencies.

Defining the problem

At the *problem-defining stage, the lecturer provided scaffolding through guiding questions, examples of problem formulation, and feedback to help students transform broad environmental issues into specific,* feasible project problems. This process encouraged students to move beyond simply identifying waste toward considering relationships among resource use, production processes, and environmental impacts. Interview findings supported this development. M1 stated, *"I do not immediately consider all leftover materials as waste. I have started to think about whether they can still be used or processed again."* Similarly, M4 noted that *"some organic waste can be reused to produce valuable products."* These responses indicate a shift from a disposal-oriented view of waste toward a resource-recovery perspective. Guiding questions were particularly important because STEM problems are often *ill-structured* and require exploration before an appropriate solution can be defined. This finding is consistent with Hathcock et al. (2015), who showed that inquiry-based questioning can provide direction for students when addressing ill-structured problems and support the development of creative solutions. Thus, scaffolding at this stage helped students clarify the problem while simultaneously recognizing potential opportunities for sustainable solutions.

Generating alternative solutions

At the *generating alternative solutions* stage, the lecturer provided scaffolding through open-ended questions, examples of possible solutions, and feedback to encourage students to generate and consider multiple alternatives. This stage strongly supported creative thinking, particularly *fluency, flexibility, originality,* and *divergent thinking*, while also providing opportunities for *risk-taking* and collaboration. Rather than immediately selecting a single answer, students were encouraged to propose different ideas, explore alternative approaches, and consider solutions beyond those initially suggested.

Interview findings indicated a shift in how students viewed leftover materials. Instead of treating them automatically as waste, students began to consider their potential for reuse as materials for value-added products. M1 stated, *"I do not immediately consider all leftover materials as waste. I have started to think about whether they can still be used or processed again."* This finding suggests that the ideation process not only expanded the range of possible solutions but also encouraged students to reconsider waste as a potential resource. From an environmental literacy perspective, this stage primarily developed environmental competencies, particularly the ability to analyze environmental problems and generate possible solutions, while beginning to strengthen behavioral strategies by translating environmental knowledge into potential actions.

Generating and comparing alternatives is an important component of creative problem solving because it allows students to move from divergent thinking toward more appropriate and feasible solutions (Lavonen et al., 2004). In the fermentation projects, students considered alternatives involving local materials, starter cultures, ingredient concentrations, and product formulations. This process is consistent with the design-oriented nature of PjBL-STEM, in which students are expected to generate, evaluate, and refine possible solutions before selecting an appropriate design. Previous studies have also reported that PjBL-STEM can enhance creative thinking by encouraging students to generate ideas and examine problems from multiple perspectives (Karina, 2024). Similarly, Wahyudi et al. (2025) found that integrating PjBL-STEM with *green chemistry* principles significantly supported the development of both *creative thinking skills* and *environmental literacy*. Thus, this stage provided an important link between idea generation, environmental problem solving, and the development of sustainable product solutions.

Analyzing constraints

At the *analyzing constraints* stage, the lecturer provided scaffolding through guiding questions, evaluation criteria, and feedback to help students consider constraints before selecting a solution, including material availability, time, cost, safety, product quality, and potential waste. This process supported flexibility, elaboration, risk-taking, and collaboration, as students were required to adapt their ideas to real-world conditions.

Interview findings indicated that students began to incorporate environmental considerations into their analysis. M3 explained that *"the group considered materials that were readily available while also paying attention to the amount of waste generated."* This response suggests that students understood project constraints not only as technical limitations but also in terms of resource availability and environmental consequences. From an environmental literacy perspective, this stage primarily developed competencies and skills, particularly the ability to analyze problems and consider the environmental consequences of decisions

The integration of authentic problem-solving and design processes in PjBL-STEM provided students with opportunities to compare alternatives and evaluate their feasibility before developing a product. This finding is consistent with Pertiwi et al. (2024), who reported that STEM-PjBL was more effective than PjBL alone in developing environmental literacy, including environmental knowledge, cognitive skills, attitudes, and behaviors. This is also supported by Fahrurrozi et al. (2026), who found that an integrated STEM-PjBL model with product differentiation significantly improved pre-service teachers' critical thinking, with qualitative evidence showing that STEM integration supported analytical reasoning. In contrast, product differentiation and reflection strengthened students' ownership and metacognitive awareness. Although their study focused on critical thinking rather than environmental literacy, these findings reinforce the importance of structured analysis and reflection in helping students evaluate alternatives and make informed decisions. Thus, *analyzing constraints* helped students move beyond generating ideas toward evaluating their feasibility, consequences, and environmental implications.

Researching information

At the *researching information* stage, the lecturer provided scaffolding through suggested sources, guiding questions, and feedback to help students identify, evaluate, and use information relevant to their projects. This stage primarily supported curiosity, fluency, flexibility, elaboration, and collaboration, as students explored different sources, compared information, and used evidence to refine their solutions.

In terms of environmental literacy, this stage mainly developed knowledge and understanding and environmental competencies, particularly the ability to use information to analyze problems and make informed decisions. Students investigated local materials, fermenting microorganisms, optimal fermentation conditions, resource use, and potential waste. They then used the information to refine product designs, enabling them to base decisions on scientific evidence rather than assumptions. This process is consistent with Pertiwi et al., (2024) who found that STEM-PjBL was more effective than PjBL alone in developing environmental literacy, including knowledge, cognitive skills, attitudes, and behaviors.

The interview findings further indicated that students began to connect technical information with resource utilization and waste reduction. M2 stated, *"underutilized materials or food residues can be processed into products with added value, so they do not immediately become waste."* This finding suggests that information seeking extended beyond technical aspects of fermentation toward understanding the environmental potential of materials. Carlina (2018) reported similar findings, showing that project-based learning incorporating environmental contexts can provide direct experiences that support students' understanding of environmental issues and the development of environmental literacy. Thus, *researching information* served as a bridge between curiosity and idea generation and evidence-based, environmentally informed decision-making.

Developing the best solution

At the *developing the best solution* stage, the lecturer provided scaffolding through solution criteria, guiding questions, design examples, and feedback to help students transform selected alternatives into more concrete solutions. This support encouraged students to modify and refine their ideas based on the information and constraints identified in earlier stages. This stage primarily supported originality, elaboration, flexibility, and risk-taking, as students were encouraged to develop distinctive ideas, elaborate their designs, and modify initial solutions when necessary.

Interview findings indicated that students began to incorporate resource utilization and waste reduction into product development. M4 stated, *"The use of local materials can be an alternative for reducing waste while optimizing the resources available in the surrounding environment."* This finding suggests that environmental considerations were increasingly integrated into the design process rather than considered only after the product was completed. Thus, students' creativity progressed from generating ideas to developing useful and more sustainable solutions.

From an environmental literacy perspective, this stage primarily strengthened environmental competencies and began to support behavioral strategies, as students translated environmental knowledge into feasible product designs. In the fermentation projects, students could modify materials, formulations, starter cultures, or production processes while considering product quality, resource use, and potential waste. This finding is consistent with (Gunawan et al., 2023) who reported that PjBL promotes authentic problem solving, idea development, and the creation of tangible products. Similarly, Mulyopratikno & Wiyarsi (2025) found that STEM-PjBL can support creativity through both the design process and the resulting products. In this process, scaffolding functioned as a bridge from initial ideas toward increasingly independent solution development, with support gradually reduced as students gained greater control over the design process. This is consistent with Hamdiyati et al. (2025), who reported that PBL supported by scaffolding can facilitate the development of creative thinking skills.

Selecting the optimal solution

At the *selecting the optimal solution* stage, the lecturer provided scaffolding through selection criteria, comparison matrices, guiding questions, and feedback to help students compare alternatives and identify the most appropriate solution. This stage primarily supported *flexibility, elaboration, risk-taking,* and *collaboration*, as students had to weigh each alternative's strengths and limitations before deciding.

Interview findings indicated that students increasingly considered sustainability when selecting solutions. M5 stated, *"The success of the product was not determined only by the fermentation results, but also by the use of readily available materials and a more environmentally friendly process."* Similarly, M3 explained that the group considered both material availability and the amount of waste generated. These responses suggest that students' criteria for an optimal solution extended beyond product quality to include resource availability, resource efficiency, waste generation, and environmental impact.

From an environmental literacy perspective, this stage primarily developed competencies/skills and behavioral strategies, as students applied environmental knowledge to decision-making. Rather than focusing solely on product quality, they considered material availability, resource efficiency, waste generation, safety, and process sustainability. The scaffolding helped students recognize that an optimal solution should satisfy product requirements while also minimizing environmental impacts. Thus, this stage served as an important bridge between environmental knowledge and sustainability-oriented decision-making. In the fermentation projects, students compared alternative materials and formulations based on product quality, material availability, the potential use of underutilized resources, and waste generation. This process reflects the STEM design principle of evaluating and selecting solutions based on defined criteria and constraints. The finding is also consistent with Wahyudi et al. (2025), who reported that PjBL-STEM integrated with *green chemistry* principles can significantly improve creative thinking skills and environmental literacy. Overall, the *selecting the optimal solution* stage provided students with opportunities to apply creative thinking while making decisions that were increasingly informed by environmental and sustainability considerations.

Planning the STEM project

At the *planning the STEM project* stage, the lecturer provided scaffolding through planning templates, procedural examples, guiding questions, and feedback to help students transform their selected solutions into systematic project plans. Students determined the materials, equipment, procedures, task distribution, timeline, and product testing methods. This stage primarily supported *elaboration, flexibility, fluency,* and *collaboration*, as students were required to develop their ideas in greater detail, adapt their plans to available conditions, and coordinate their work within the group.

Interview findings indicated that sustainability considerations developed during the earlier stages were incorporated into project planning. M3 stated that *"the group considered materials that were easily available while also paying attention to the amount of waste generated."* This suggests that considerations related to material use and waste were not limited to evaluating the final product but became part of the planning process itself. The scaffolding therefore helped students integrate technical and environmental considerations into their project design.

From an environmental literacy perspective, this stage primarily strengthened competencies/skills and behavioral strategies, as students began to plan concrete actions while considering resource use, material efficiency, and waste management. Through gradual support, students were guided to develop more systematic and increasingly independent project plans. This finding is consistent with Pertiwi et al. (2024), who reported that STEM-PjBL provides project-based learning experiences that can support environmental literacy across knowledge, cognitive skills, attitudes, and behavioral dimensions. Thus, the *planning stage of the STEM project* provided an important opportunity for students to translate environmental knowledge and sustainability considerations into concrete action plans.

Developing the STEM product

At the *developing the STEM product* stage, the lecturer provided scaffolding through demonstrations, procedural guidance, guiding questions, and feedback throughout the product development process. This support helped students translate their designs into tangible fermentation products and adjust when results did not meet their expectations. The stage primarily supported *originality, elaboration, flexibility, risk-taking,* and *collaboration*, as students developed their ideas, modified their designs, explored alternatives, and worked collaboratively to address emerging challenges.

Interview findings suggest that the product development process strengthened students' shift from a disposal-oriented perspective toward the reuse and recovery of resources. M1 stated, *"I no longer automatically consider all leftover materials as waste. I started to think about whether they could still be used or processed further."* Similarly, M4 noted that *"some organic waste can be reused to produce valuable products."* These responses indicate that hands-on experience in developing fermentation products provided a concrete context for students to apply the principle of *resource recovery*. This shift was further reflected in M5's statement that *"a good product uses resources efficiently and produces less waste."* This finding suggests that students began to evaluate product quality not only by successful fermentation outcomes but also by resource efficiency and waste generation.

From an environmental literacy perspective, this stage primarily developed competencies/skills and behavioral strategies, as students translated environmental knowledge into practical action. During product development, students considered local and underutilized materials, material efficiency, and potential waste throughout the production process. Thus, *scaffolding* helped students transform creative ideas into tangible products while integrating sustainability considerations into the design process. This finding is consistent with Pertiwi et al. (2024), who reported that STEM-PjBL was more effective than conventional PjBL in developing environmental literacy across knowledge, cognitive skills, attitudes, and behavioral dimensions. It also aligns with Wahyudi et al. (2025), who found that PjBL-STEM integrated with *green chemistry* significantly enhanced both creative thinking skills and environmental literacy. Similarly, Raoufi et al. (2019) demonstrated that hands-on, team-based product design can help students understand sustainable product development by considering environmental impacts during design and manufacturing decisions. In the present study, scaffolding further supported this process by guiding product development while allowing students to make and revise their own decisions. This is consistent with Schutte et al. (2026), who emphasized that scaffolding in sustainability-oriented project learning should guide students' thinking and decision-making while maintaining opportunities for autonomy.

Testing, refining, communicating, and reflecting on the project outcomes

At the *testing, refining, communicating, and reflecting on the project outcomes* stage, the lecturer provided scaffolding through testing rubrics, reflective questions, feedback, and evaluation guidance to support students in testing, improving, communicating, and reflecting on their project outcomes. When the product did not meet the expected criteria, students were encouraged to identify possible causes, generate alternative improvements, and retest their products. This iterative process primarily supported *elaboration, flexibility, originality, risk-taking,* and *collaboration*.

From an environmental literacy perspective, this stage primarily supported competencies/skills, cognitive and affective dispositions, and behavioral strategies. Students were encouraged to evaluate not only product quality but also material use, resource efficiency, waste generation, and the potential environmental consequences of their production processes.

Interview findings further indicated that reflection encouraged students to adopt a broader perspective on sustainability. M2 stated, *"Product development needs to consider its environmental impact, not only the outcome."* Similarly, M5 emphasized that *"a good product uses resources efficiently and produces less waste."* These responses suggest that students increasingly evaluated product quality holistically, considering resource efficiency, waste reduction, and environmental impact alongside technical performance.

Thus, *scaffolding* helped students connect their project experiences with their environmental consequences, extending environmental literacy beyond conceptual understanding toward sustainability-oriented decision-making and action. Reflection also encouraged students to evaluate their previous decisions, identify weaknesses, and consider improvements for future projects. This process helped students recognize that successful product development depends not only on the quality of the final product but also on the efficiency and environmental responsibility of the production process. This finding is consistent with Geithner & Menzel (2016), who demonstrated that experiential and reflective learning can strengthen conceptual knowledge, teamwork, and action-oriented learning through authentic project experiences. Similarly, Miranda et al. (2020) reported that active, experiential, and reflective PjBL can support the development of problem-solving, creativity, communication, and lifelong learning skills. In the present study, these experiential and reflective processes were further connected to environmental considerations, enabling students to evaluate both product outcomes and the environmental implications of their decisions. The finding is also consistent with Wahyudi et al. (2025), who reported that integrating PjBL-STEM with *green chemistry* principles can enhance both creative thinking skills and environmental literacy.

Overall, the findings highlight the potential of Scaffolded PjBL-STEM through sustainable fermentation product design as a meaningful approach to simultaneously support the development of creative thinking skills and environmental literacy among prospective biology teachers. The findings suggest that integrating authentic problems, STEM design processes, and gradual scaffolding can provide students with opportunities to generate and develop ideas, make evidence-based decisions, and consider environmental consequences throughout the product development process. These results have practical implications for biology and microbiology education, particularly in shifting laboratory learning from cookbook-oriented activities toward more authentic, problem-based, and sustainability-oriented learning experiences. However, the findings should be interpreted in light of several limitations. The study employed a one-group pretest-posttest design without a comparison group. It involved a relatively small sample of 19 students from a single study program, which limits the generalizability of the findings and does not allow strong causal conclusions. In addition, the intervention was implemented over a limited period, which may not have been sufficient to capture sustained changes, particularly in the behavioral dimension of environmental literacy. Future studies should therefore use larger, more diverse samples, include comparison groups, and use longitudinal designs to examine the sustainability of changes in creative thinking skills and environmental literacy. Further research could also strengthen the environmental dimension of the projects by explicitly incorporating life-cycle considerations, resource efficiency, waste reduction, and environmental impact assessment into the STEM design process.

CONCLUSION

This study demonstrates that STEM-integrated *Scaffolded Project-Based Learning* through sustainable fermentation product design can serve as a meaningful instructional approach for developing creative thinking skills and environmental literacy among university students. Rather than positioning students as passive recipients of fermentation concepts, the learning process engaged them in authentic experiences involving problem identification, exploration of alternative solutions, product design and testing, evaluation of outcomes, and consideration of resource utilization and environmental impacts. Sustainable fermentation projects can thus bridge microbiology concepts with real-world problems while giving students opportunities to develop essential 21st-century competencies.

The findings further indicate that scaffolding is an important component in supporting this learning process. Gradually provided prompts and guiding questions enabled students to cope with the complexity of the projects without taking over their thinking processes. Students progressively moved from relying on guidance to identify problems and develop designs toward greater independence in evaluating alternatives, solving problems, and making decisions. Integrating STEM with fermentation projects also created a context in which creative thinking could develop through design and experimentation. At the same time, environmental literacy was fostered through consideration of material utilization, waste reduction, resource efficiency, and sustainability.

Nevertheless, developing environmental literacy, particularly its behavioral dimension, may require more sustained learning experiences and longer periods of engagement. Future research should therefore investigate longitudinal projects to examine the sustainability of changes in environmental behavior, incorporate comparison or control groups, and involve larger, more diverse samples. Project development could also be extended to include systematic assessments of the environmental impacts of fermentation products, material-use efficiency, waste reduction, and the application of developed products in authentic real-world contexts.

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