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Project-Based Learning (PjBL) Integrated with STREAM-ESD in Kombucha Tea Production to Enhance Students' Critical Thinking Skills

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Abstract

This study aims to examine the effectiveness of STREAM-integrated Project-Based Learning This study investigates the effectiveness of a Project-Based Learning (PjBL) model integrated with the STREAM–ESD (Science, Technology, Religion, Engineering, Arts, Mathematics – Education for Sustainable Development) approach in enhancing junior high school students' critical thinking skills within the topic of biotechnology. Utilizing a quasi-experimental design, the research was conducted on Grade IX students in South Cianjur, West Java, through a kombucha tea production project grounded in real-world application and interdisciplinary inquiry. The intervention involved four stages: problem definition, data collection, building, and utilization. Results from pretest and posttest assessments revealed a significant increase in critical thinking skills in the experimental group (N-Gain = 0.7057, high category) compared to the control group (N-Gain = 0.4514, moderate category), with statistical tests confirming a meaningful difference ($p < 0.05$). The findings demonstrate that the integration of STREAM and ESD into PjBL fosters analytical thinking, creativity, and moral reasoning through contextual learning experiences. Moreover, the inclusion of ethical and religious perspectives encouraged students to consider the social and spiritual implications of scientific practices. This research contributes to the ongoing discourse on educational innovation by offering a sustainable, student-centered, and culturally responsive model for science education aligned with the goals of Indonesia Emas 2045 and the UN Sustainable Development Goals

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INTRODUCTION

The shift in 21st-century education has sparked a significant transformation in learning paradigms. Traditional teacher-centered approaches are gradually being replaced by student-centered learning models that emphasize adaptability, inquiry, collaboration, and real-world relevance (Mansyur *et al.*, 2024). The rapid advancement of information technology and the growing complexity of global challenges demand that students not only master academic content but also develop 21st-century competencies—most notably, critical thinking. These skills are essential for individuals to analyze problems, make informed decisions, and construct logical arguments in diverse life contexts . However, educational practices in Indonesia, particularly in science subjects such as biotechnology, have not fully adopted these competencies. The conventional approach remains dominant, often characterized by rote memorization, didactic teaching, and limited opportunities for student exploration (Afidah *et al.*, 2023)

Science lessons still prioritize content delivery rather than skill development. This issue is especially problematic in biotechnology topics such as fermentation, where students frequently face difficulties in understanding abstract concepts. Factors such as limited laboratory infrastructure, lack of contextual application, and inadequate teaching resources contribute to persistent misconceptions and disengagement (Shafira *et al.*, 2025). Preliminary studies at junior high schools in rural areas like South Cianjur, West Java, reveal alarming trends. A significant portion of students (36.31%) harbor misconceptions about fermentation, often believing that all microorganisms are harmful or that biotechnology is limited to genetic manipulation (Aliyyah *et al.,* 2020). Furthermore, 32.9% of students view biotechnology as a challenging topic, demonstrating low confidence and limited conceptual understanding. These findings suggest a pressing need to innovate science education, particularly through approaches that link scientific knowledge with real-life experiences and student inquiry.

Critical thinking, as a higher-order cognitive skill, enables learners to interpret information accurately, evaluate sources, analyze arguments, and draw evidence-based conclusions. Developing these skills is crucial for scientific literacy and lifelong learning . Numerous studies have emphasized that critical thinking should be fostered early and consistently across educational levels, especially in science education, where students must process complex data and construct explanations for natural phenomena

To address these challenges, researchers and educators have begun to adopt interdisciplinary models such as STREAM (Science, Technology, Religion, Engineering, Arts, and Mathematics), which aim to integrate cognitive, affective, and practical domains of learning. STREAM encourages learners to explore scientific concepts through a holistic lens while embedding values of ethics, sustainability, and creativity . When combined with Project-Based Learning (PjBL), this model offers an innovative pathway to deepen understanding and foster critical thinking through student-led, authentic learning tasks (Rozi et al., 2025; (Meha, 2021); (Febril *et al.*, 2022)) PjBL is grounded in constructivist theory, which posits that learners actively build knowledge through experience and reflection. By engaging in meaningful projects, students not only apply scientific knowledge but also engage in inquiry, analysis, problem-solving, and decision-making. This learning model aligns with the needs of 21st-century learners, offering a rich context to nurture critical thinking skills. Dori and Belcher (2005) emphasized that PjBL fosters reflective thinking, where students are encouraged to analyze and evaluate solutions, consider alternative perspectives, and make informed judgments.

The integration of STREAM and PjBL is further strengthened when contextualized within Education for Sustainable Development (ESD), which emphasizes social responsibility, environmental awareness, and ethical reasoning. According to (Takiddin e*t al.*, 2020).), combining ESD with PjBL-STREAM enhances the relevance of science education by aligning learning objectives with global and local sustainability challenges. In practice, this model empowers students to connect science with real-world issues, critically assess their impact, and take action based on evidence and reflection.

A concrete example of such contextualized learning is the use of kombucha fermentation projects in junior high schools. This project incorporates local tea leaves and natural resources to study microbial activity and fermentation processes. It allows students to explore scientific phenomena while engaging in hands-on activities with direct environmental and social relevance. The project also introduces students to sustainable

practices, such as recycling fruit waste and producing organic fertilizer from SCOBY (Symbiotic Culture of Bacteria and Yeast), reinforcing systems thinking and ethical decision-making in biotechnology (Habibah *et al.*, 2022). Previous research supports the efficacy of this integrated model. (Rahardhian, 2022) demonstrated that PjBL integrated with ESD significantly enhances students' critical thinking by offering opportunities to reflect on real-life problems, collaborate with peers, and design scientific solutions. Similarly, (Monika & Rahmasari, 2023) found that students' critical thinking develops more rapidly when they engage in authentic scientific inquiry and product-based learning tasks that simulate professional practice.

Moreover, the integration of religious and ethical values within the STREAM framework introduces a moral dimension to science education. showed that embedding spiritual perspectives in learning enhances students' ability to evaluate scientific problems not only through a logical lens but also from an ethical standpoint. This is particularly important in biotechnology, where ethical dilemmas often arise (Halimah *et al.,* 2023). By incorporating religious elements, students are encouraged to think deeply about the implications of scientific innovation for human well-being and the environment.In this context, teaching strategies that combine STREAM, PjBL, and ESD provide a multidimensional approach to science learning. Students are not only expected to grasp scientific theories but also to apply them in designing innovative products, reflecting on their decisions, and evaluating outcomes based on evidence and social values. According to (Triprani *et al.,* 2023), such models are effective in bridging the gap between abstract knowledge and real-life application, enabling students to construct meaning and engage in purposeful learning.

In Indonesia's current education landscape, the integration of STREAM and ESD remains underutilized. Most science classrooms still rely on textbook-based instruction, leaving little room for student inquiry, experimentation, and interdisciplinary learning (Azizah *et al.*, 2019). This research is motivated by the need to fill this gap, particularly by developing science learning experiences that are relevant, interactive, and impactful. Through the implementation of a kombucha-based project within the STREAM-ESD-PjBL framework, this study offers a practical model to enhance students' critical thinking in biotechnology topics, while addressing local resource utilization and sustainability education (Nadya *et al*., 2024).

In alignment with the vision of Indonesia Emas 2045 and the United Nations' Sustainable Development Goals (SDGs), this approach reflects an educational innovation that supports the development of responsible, reflective, and capable young citizens. The integration of scientific knowledge with ethical, environmental, and cultural perspectives prepares students not only for academic success but also for meaningful participation in society (Kajian *et a*l., 2022) .

Therefore, this study seeks to explore the effectiveness of the PjBL model integrated with STREAM-ESD in fostering students' critical thinking in biotechnology learning. By engaging students in the real-world task of kombucha tea production, the model encourages inquiry, reflection, and interdisciplinary understanding. This research contributes to the growing body of literature that advocates for reform in science education through contextual, holistic, and student-centered approaches that are both innovative and culturally responsive. This research offers a novel contribution by integrating sustainability issues, local resource utilization, and interdisciplinary learning into science education, aligning with the vision of Indonesia Emas 2045 and global educational goals.

RESEARCH METHOD

This study employed a quasi-experimental design with a pretest-posttest control group format. The research was conducted from February to April 2025 at a public junior high school in South Cianjur, West Java, Indonesia. The population consisted of Grade IX students, and two parallel classes were selected using purposive sampling. One class was assigned as the experimental group, which received Project-Based Learning (PjBL) integrated with STREAM-ESD through a kombucha tea production project. The other served as the control group and received conventional instruction. The research procedure involved four stages: (1) preparation and development of learning materials based on the STREAM-ESD framework, (2) implementation of teaching interventions over four meetings, (3) administration of pretests and posttests, and (4) analysis and interpretation of results. Instruments included a critical thinking skills test (Multiple Coice), and

observation sheet. Data were analyzed using descriptive statistics and inferential tests, including normality, homogeneity, and paired sample t-tests, to determine the effectiveness of the intervention. All analyses were conducted using SPSS version 26.

RESULTS AND DISCUSSION

This study aimed to examine the improvement of students' critical thinking skills after participating in biotechnology learning through the production of kombucha tea using a Project-Based Learning (PjBL) model integrated with the STREAM approach. Measurements were conducted using pretests and posttests in both the experimental and control classes. The quantitative data on students' critical thinking skills were analyzed using both descriptive and inferential statistical methods.

Based on the pretest results, the average critical thinking score in the experimental class was 65.0, which increased to 86.00 in the posttest. In contrast, the control class also started with a pretest average of 55.0 but only improved to 69.09 in the posttest. These results indicate a more substantial improvement in the experimental class compared to the control class.

This improvement is further illustrated in Figure Table 1 , which present the average pretestand posttest scores. The more significant increase in the experimental class demonstrates that the implementation of STREAM-integrated PjBL successfully fostered students' critical thinking in a practical context, particularly in the scientific and interdisciplinary design and evaluation of kombucha tea production projects.

Tabel 1. Average Scores of Pretest and Posttest in Experimental and Control Classes

Group	Average Pretest	Average Posttest	Improvement
Control	55.00	69.00	12.53
Experimental	65.00	85.83	33.33

To test the hypothesis, an independent sample t-test was conducted. This test aimed to determine whether there was a statistically significant difference in the critical thinking skills between the experimental class and the control class after the intervention. Analysis of N-Gain Scores and Learning Effectiveness. To further evaluate the learning outcomes, a normalized gain (N-Gain) analysis was conducted on both the experimental and control groups. N-Gain analysis provides insight into the instructional effectiveness by measuring the relative improvement in students' scores from pretest to posttest. The classification of N-Gain scores follows the criteria proposed by (Hehakaya et al., 2022), as shown below:

Table 2. N-Gain Criteria Classification

N-Gain Score Range	Category
N-Gain ≥ 0.70	High
$0.30 <$ N-Gain ≤ 0.70	Moderate
N-Gain < 0.30	Low

Based on this classification, the results of the N-Gain analysis for this study are summarized as follows:

Table 3. Average N-Gain Scores of the Experimental and Control Classes

Class	N-Gain	Category
Experimental	0.7057	High
Control	0.4514	Moderate

As presented in Table 3, the average N-Gain score in the experimental class was 0.7057, which falls into the high category. In contrast, the control class achieved a moderate gain of 0.4514. This substantial difference suggests that the STREAM-integrated PjBL model implemented in the experimental class was more effective in enhancing students' learning outcomes compared to the regular PjBL approach used in the control group.

This finding illustrates that engaging students in authentic activities—such as the kombucha tea production project—offered greater opportunities for exploration, collaboration, and contextual application of scientific concepts. Such activities align with the constructivist principles of science learning, where knowledge is constructed through meaningful experience. Sa'dijah et al. (2021) affirm that active involvement in project-based learning significantly improves conceptual understanding and fosters higher-order thinking skills. Similarly, Putri et al. (2023) highlight the STREAM model's ability to accommodate diverse learning styles while stimulating both critical and creative thinking. The integration of arts in STREAM, as noted by Rahmawati & Ridwan (2022), further enhances flexibility in thought and innovation among students.

Table 4. N-Gain Percentage Scores of the Experimental and Control Classes

Class	N-Gain Percentage	Effectiveness Category
Experimental	71%	Effective
Control	45%	Less Effective

According to Table 4, the experimental class achieved a normalized gain percentage of 71%, categorized as effective, while the control class scored only 45%, which is deemed less effective. This highlights the varying degrees of instructional impact between the two teaching models. Retnowati et al. (2020) argue that the effectiveness of a learning approach is highly influenced by its ability to connect academic content to students' real-life experiences. In this context, STREAM-based learning—encompassing Science, Technology, Engineering, Arts, and Mathematics—has proven to be particularly engaging and multidimensional, addressing not only cognitive domains but also affective and psychomotor aspects (Hendriana & Sofyan, 2022).

These findings support the notion that interdisciplinary project-based learning grounded in STREAM principles significantly improves student learning outcomes and enhances the overall instructional effectiveness. The notable gains in the experimental group not only reflect improved academic performance but also point to a deeper development of critical thinking and creativity—skills essential for 21st-century learners.

To statistically validate whether the difference between the groups' learning outcomes was significant, an independent sample t-test was conducted, as described in the next section. The results of the t-test are presented in Table 5

Table 5. Independent Sample t-Test Results of Students' Critical Thinking Skills

No	Aspect	Test	Significance	Criteria Significance	Descriptiom
1.	Critical thinking skill	Pre-test	**0.000**	**0,05**	Significantly Different
		Post-test	**0.000**	**0,05**	Significantly Different

The analysis results in Table 5 show that the significance value (Sig. 2-tailed) is 0.000, which is lower than the threshold of 0.05. This indicates that there is a statistically significant difference in critical thinking skills between students who were taught using STREAM-integrated PjBL and those who received conventional instruction. These findings confirm that the STREAM-based approach combined with real- world project implementation (i.e., fruit-flavored kombucha production) contributed positively to students' cognitive engagement. This model provides meaningful learning experiences that promote higher-order thinking, such as analyzing, evaluating, and drawing conclusions across disciplines—aligned with the demands of 21st-century education . Furthermore, this result is in line with studies by (Sri Kuwita Gandi *et al., 2021)* , which emphasize that active and interdisciplinary learning strategies can significantly enhance students' critical thinking capacities, especially when contextualized within sustainability issues (Syukri et al., 2013).

The findings of this study indicate that Project-Based Learning (PjBL) integrated with the STREAM–ESD approach significantly enhanced students' critical thinking skills (Sri Kuwita Gandi *et al.*, 2021) . This improvement is clearly reflected in the experimental group's average score, which increased from 65.0 in the pretest to 85.83 in the posttest. In contrast, the control group only rose from 55.0 to 69.09. The N-Gain analysis further supports this outcome, with the experimental group scoring 0.7057 (high category), while the control group attained 0.4514 (moderate category).

This significant increase in the experimental group suggests that the contextual, collaborative, and interdisciplinary kombucha tea project effectively stimulated students' higher-order thinking processes. Throughout the project, students not only learned about fermentation but were also involved in designing, testing, and evaluating the product they created (Sahrir *et al.*, 2024). These experiences provided meaningful opportunities to analyze problems, evaluate alternative solutions, and draw conclusions based on empirical data—core components of critical thinking (Takiddin *et al.*, 2020).

The STREAM model in science education plays a vital role in improving critical thinking by integrating science, technology, engineering, arts, and mathematics in real-world contexts. Engaging students in the kombucha project required them to think systematically across disciplines—from testing pH, understanding microbial roles, to calculating ingredient ratios and analyzing outcomes. Such activities strengthened critical thinking through phases of observation, data collection, interpretation, and informed decision-making (Rahman & Na, 2024)

The success of STREAM-based project learning also aligns with constructivist principles, where knowledge is actively constructed through direct experience. When students observe and reflect on the results of the fermentation process firsthand, they are driven to think critically and deeply about the concepts learned (Dr. Ifada Novikasari, S.Si., 2024) . This supports findings by (Sahrir et al., 2024) which reported that interdisciplinary project-based science learning is more effective in fostering students' critical thinking compared to traditional instruction.

Moreover, the independent sample t-test confirmed that the difference in students' critical thinking skills between the experimental and control groups was statistically significant ($p < 0.05$). This result validates the effectiveness of the STREAM–ESD-integrated PjBL model in fostering cognitive engagement and enhancing critical thinking (Fadhilah, 2022). It demonstrates that contextual projects like kombucha production not only improve conceptual understanding but also promote critical inquiry and independent reasoning (Indayani *2023)*

These findings support the argument that interdisciplinary project-based learning using real-world contexts is highly effective in developing students' critical thinking in biotechnology education. Problem-based activities such as kombucha production allow students to explore, reason, and draw conclusions independently—essential skills in addressing the challenges of 21st-century education (Naufal & Rizki, 2025)

The significant improvement in critical thinking skills observed in the experimental class indicates that

the project-based learning model integrated with the STREAM–ESD approach demonstrates substantial effectiveness compared to conventional methods. This effectiveness is evident not only statistically but also in its theoretical foundations and accompanying pedagogical practices. Several key aspects support the success of this approach in cultivating higher-order thinking skills in students.

This approach places students in an authentic real-world learning context. The kombucha tea production project, as the core of the learning activity, requires students to design, conduct experiments, take measurements, interpret data, and draw conclusions based on their findings. These activities involve not only conceptual knowledge but also direct engagement in scientific processes. This aligns with constructivist theory, which emphasizes that knowledge is actively built by learners through meaningful experience and reflection (Dori & Belcher, 2005). Through this project, students move beyond merely following procedures to actively evaluating the fermentation process, understanding pH changes, and analyzing the proportion of ingredients and final outcomes (Nisak, 2023). The application of experiential, real-world projects has proven effective in fostering deep analytical and reflective thinking—two core components of critical thinking.

The STREAM model provides a robust interdisciplinary framework in science education. By integrating Science, Technology, Engineering, Arts, Mathematics, and also Religious and Ethical elements, this approach enriches students' perspectives and problem-solving strategies. Learning is no longer linear or fragmented but unified into a comprehensive whole. As noted by (Studi *et al.*, 2023) the integration of ESD into PjBL within science learning can address cognitive, affective, and psychomotor aspects in a balanced way. also stated that STREAM provides space for diverse learning styles and encourages both critical and creative thinking. The involvement of arts in the design and presentation of kombucha products, as explained by (Siswantara *et a*l., 2023), broadens students' thinking horizons and promotes flexibility in decision- making. This was evident in students' creativity in designing kombucha flavor variations that were not only tasty but also considered aesthetics and environmental factors.

The success of this learning model is inseparable from the inclusion of ethical and religious dimensions in the biotechnology learning process. This approach explicitly invites students to reflect on the fermentation process not only from a scientific perspective but also from a religious standpoint, particularly regarding the permissibility (halal) of ingredients and final products (Bouzenita, 2022). Students are encouraged to consider whether the fermented product contains ethanol levels beyond what is permissible in Islam, and how to understand microorganisms from the perspective of ethical consumption.

Research by (Buana *et al*., 2023) revealed that the integration of spiritual values in science learning enhances students' moral reasoning abilities. In this context, students learn about biotechnology not only as a scientific discipline but also as a practice that must be socially and religiously accountable. Such learning aligns not only with the principles of 21st-century education but also cultivates self-awareness and empathy in scientific decision-making (Ma'wa *et al.*, 2022).

The learning steps in this project were implemented using the PDBU approach (Problem Definition – Data Collection – Building – Utilization). In the first stage, students defined the problem related to the lack of understanding about fermentation and the application of simple biotechnology in everyday life (Sahrir *et al.*, 2024). In the second stage, students conducted data collection through literature review, observation of local natural ingredients, and initial measurements such as the pH of Campaka tea as a base material. The third stage, Building, involved students designing and producing kombucha tea with fruit flavor innovations, monitoring the fermentation process, and recording the outcomes. Finally, in the Utilization stage, students presented their products, conducted taste testing, and reflected on the social, economic, and religious values of the resulting product. This process demonstrated a complete cycle of critical thinking—from problem identification to the assessment of solution impacts.

Through the PDBU approach within the STREAM–ESD framework, students not only developed conceptual understanding of fermentation but also skills in managing information, solving problems, and evaluating solutions based on scientific and ethical values. This embodies the essence of developing 21st-century critical thinking skills as envisioned in science education reform (Agustina *et al*., 2020). In conclusion, the findings clearly demonstrate that the integration of Project-Based Learning with the STREAM–ESD framework significantly enhances students' critical thinking skills in biotechnology learning (Okolie *et al*.,

2021) . The experimental group, which engaged in a contextual kombucha fermentation project, exhibited not only higher average scores and gain indexes but also deeper engagement in interdisciplinary thinking, ethical reflection, and scientific reasoning. This aligns with the goal of the study, which was to examine whether STREAM-integrated PjBL could effectively foster students' critical thinking. The substantial improvements across multiple assessment dimensions confirm the success of the intervention in equipping students with higher-order thinking skills essential for 21st-century education.

CONCLUSION

This study concludes that the Project-Based Learning (PjBL) model integrated with the STREAM–ESD approach is highly effective in improving junior high school students' critical thinking skills in biotechnology education. The statistically significant difference in learning outcomes between the experimental and control groups—supported by high normalized gain and active student involvement—validates the impact of this interdisciplinary, value-oriented, and contextual learning model.

Through the kombucha tea production project, students not only learned scientific concepts related to fermentation but also practiced problem-solving, ethical decision-making, and sustainability reflection within real-world contexts. The use of the PDBU (Problem Definition – Data Collection – Building – Utilization) framework further reinforced a structured critical thinking process, from identifying problems to evaluating the outcomes of their solutions.

Moreover, the STREAM–ESD integration enriched science education by linking cognitive, affective, and moral learning domains, bridging abstract scientific theory with practical application and personal relevance. The inclusion of religious and ethical considerations strengthened students' moral reasoning and empathy in addressing scientific challenges.

Overall, this study provides compelling evidence that PjBL integrated with STREAM–ESD is an innovative and culturally responsive model for science instruction. It equips students with the competencies necessary for 21st-century challenges, fosters meaningful engagement, and supports national and global education goals such as Indonesia Emas 2045 and the Sustainable Development Goals (SDGs). Future implementations and research are encouraged to adopt and adapt this model to various scientific topics and local contexts to maximize its transformative potential.

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