ISEJ Indonesian Science Education Journal

ISSN Online: 2716-3350
https://siducat.org/index.php/isej/
Published by Yayasan Darussalam Bengkulu

OPEN ACCESS ARTICLE

Development of Biotechnology E-Module Based on Project-Based Learning Integrated with Betawi Local Wisdom to Enhance Creative Thinking Skills

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Received: March 15, 2028	Revised: May 13, 2026	Accepted: June 12, 2026

Abstract
This study aims to develop an e-module based on Project Based Learning (PjBL) integrated with Betawi local wisdom on biotechnology topics that is valid, practical, and effective in improving students' creative thinking skills. The e-module was developed using the 4D model (Define, Design, Develop, and Disseminate). The trial was conducted with 69 eleventh-grade senior high school students. The validity of the e-module was assessed by three experts based on content, presentation, and language aspects, while its practicality was evaluated through student response questionnaires, and learning implementation observation sheets. The effectiveness of the e-module was measured using a creative thinking skills test, which was analyzed using N-gain and paired sample t-test. The results showed that the e-module obtained an average validity score of 92%, categorized as highly valid. The practicality results based on student responses, and learning implementation observations indicated that the e-module was highly practical. The effectiveness analysis showed an improvement in students' creative thinking skills with an average N-gain score of 0.65, categorized as moderate. The N-gain scores for fluency, flexibility, originality, and elaboration were 0.69, 0.77, 0.52, and 0.60, respectively with categories ranging from moderate to high. The paired sample t-test results indicated a significant difference between pretest and posttest scores ($p < 0.05$). Based on these findings, it can be concluded that the Project Based Learning (PjBL)-based e-module integrated with Betawi local wisdom on biotechnology topics is highly valid, highly practical, and effective to enhance students' creative thinking skills.

Keywords: E-Module; Project-Based Learning; Betawi Local Wisdom; Biotechnology; Creative Thinking

INTRODUCTION

Biotechnology is a biology subject that requires students not only to to grasp theoretical knowledge but also to integrate scientific concepts with problem-solving processes and actionable product development in real-life contexts (Pantiwati et al., 2022). Given its practical, multidisciplinary, and product-oriented nature, biotechnology has great potential to be delivered through learning models that provide students with authentic experiences. (Indriyanti et al., 2025). Therefore, biotechnology instruction needs to provide learning experiences that involve product investigation, design, testing, and evaluation so that students can develop higher-order thinking skills. However, initial observations and interviews with biology teachers at SMAN 98 Jakarta indicate that biotechnology learning still faces challenges in providing learning experiences oriented toward creative thinking skills development. While the current teaching practices have supported the understanding of basic biotechnology concepts, activities that encourage students to generate innovative ideas, explore alternative solutions, and design biotechnology products remain limited. Consequently, the development of students' creative thinking skills has not yet been optimized.

Creative thinking skill is the ability to generate original, useful, and innovative ideas through imaginative, flexible, and evaluative thinking when faced with a problem (Akbar et al., 2025; Munandar, 2012; Sternberg & Kaufman, 2018). Creative thinking skills can be identified through four indicators: fluency, which is the ability to generate numerous ideas; flexibility, the use of diverse approaches to problem-solving; originality, the capacity to produce unique ideas; and elaboration, which demonstrates the ability to develop and detail a concept. (Torrance, 1974).

One way to develop students' creative thinking skills is by implementing the Project-Based Learning (PjBL) model (Suyono et al., 2025). This model encourages contextual problem-solving, enabling students to explore, interpret, and develop products, thereby effectively fostering creative thinking skills (Fitri et al., 2024). Wafiyah dkk. (2025) also found in their study that the groups of students learning through PjBL achieved higher levels of creative thinking compared to groups learning through conventional methods. The implementation of PjBL will be more effective if it is supported by digital learning materials capable of guiding students throughout the learning process. E-Modules offer a solution through their ability to combine text, illustrations, animations, videos, and practice exercises, thereby visualizing abstract biological concepts that are difficult to observe directly and supporting students' independent learning. (Fatma et al., 2025). The PjBL-based e-module also functions as a learning guide to help students investigate, document project steps, and evaluate developed products. Integrating PjBL syntax provides a systematic structure through planning, investigating, processing information, and reflecting on project results, ensuring students achieve a more contextual and meaningful learning experience.. (Andari & Lusiana, 2025; Praptama et al., 2023; Purnamasari et al., 2025). In addition, PjBL-based e-modules can also encourage students to improve their creative thinking skills by generating ideas and solutions for projects (Nuralita dkk., 2025). Thus, PjBL-based e-modules can serve as learning materials that support the creation of biotechnology instruction that is more active, contextual, and oriented toward the development of creative thinking skills.

Besides appropriate models and teaching materials, biotechnology learning is more meaningful when linked to real-world scenarios by incorporating local wisdom. This integration transforms abstract scientific principles into concrete, meaningful, and relevant experiences, thereby facilitating a better understanding of the scientific concepts under study (Rosyidah et al., 2025; Yanto et al., 2025). The integration of Project-based Learning and local wisdom also improves students' creative thinking skills and learning outcomes in each cycle (Almubarokah & Chamdani, 2025).

One of the local wisdoms in Jakarta that is closely linked to biotechnology concepts is *roti buaya* (crocodile bread). *Roti buaya* is a traditional Betawi food product that holds cultural value, particularly in wedding traditions, where it serves as a symbol of fidelity and the hope for a sustainable marital life. (Sihotang et al., 2019; Siregar & Yahaya, 2022). Choosing *roti buaya* as an instructional context extends beyond its cultural significance; it directly connects to the principles of conventional biotechnology. The production process utilizes microorganisms, namely yeast (*Saccharomyces cerevisiae*), driven by fermentation that transforms the structural characteristics of the dough (Zhao et al., 2023). This context provides an opportunity for students to study fermentation concepts tangibly while simultaneously developing product innovations through project activities. Through the *roti buaya* innovation project, students can enhance their creative thinking skills by designing product modifications, exploring various alternative ingredients or presentation forms, and considering cultural values in product development. Consequently, the integration of Betawi local wisdom in the form of *roti buaya* provides a strong cultural, pedagogical, and curricular foundation in biotechnology instruction.

Various studies have developed e-modules, Project-Based Learning (PjBL), and local wisdom-based learning in biology education. The development of PjBL-based e-modules for biology topics has shown potential in improving learning quality by providing digital instructional materials that support project activities (Aliyah & Widiyatmoko, 2023). Regarding biotechnology topics, numerous researchers have also designed project-based instructional materials to foster both students' conceptual comprehension and practical skills. (Husna et al., 2023). Furthermore, incorporating local wisdom within biology education is increasingly developed to bridge scientific principles with real-life scenarios and foster student creativity. (Lestari & Ikhsan, 2025; Perdana et al., 2024)

Although numerous studies have been conducted on E-Modules, PjBL, creative thinking skills, and local wisdom-based learning, but research that integrated PjBL, Betawi local wisdom, and creative thinking skills into a single E-Module for biotechnology topics remains very limited. Given this gap, this study offers novelty through the development of a biotechnology e-module based on Project-Based Learning that integrates Betawi local wisdom and is specifically directed at enhancing students' creative thinking skills. Unlike previous studies that generally developed e-modules, PjBL, or local wisdom separately, this research combines these three components into a single digital instructional material designed through authentic project activities. The use of *roti buaya* as a project context provides a learning experience that connects conventional biotechnology concepts, Betawi cultural values, and the process of developing creative ideas through product innovation.

Thus, this study not only produces an e-module as a digital learning resource but also presents a contextual instructional design that facilitates students in understanding biotechnology concepts while developing creative thinking skills through processes of exploration, design, and product creation. Therefore, this study aims to develop a Project-Based Learning e-module integrated with Betawi local wisdom for biotechnology topics and to test its validity, practicality, and effectiveness in enhancing students' creative thinking skills.

METHODS

This study falls under the category of research and development (R&D). The development model used is the 4D model proposed by Thiagarajan et al. (1974). This model consists of four main stages: Define, Design, Develop, and Disseminate. The 4D model was chosen because it is systematic, structured, and suitable for the development of learning tools such as E-Modules (Rusmanto & Rukun, 2020). The 4D model was used to produce a biotechnology e-module based on Project Based Learning (PjBL) integrated with Betawi local wisdom to enhance students' creative thinking skills.

The Define stage was conducted to identify learning needs and the requirements for developing the e-module. This stage included curriculum analysis, student characteristics analysis, concept analysis, and task analysis. Curriculum analysis was conducted to determine the alignment of biotechnology content with the learning outcomes of the Merdeka Curriculum. Student analysis was performed through observations and interviews with biology teachers to identify students' learning characteristics and difficulties in biotechnology learning. Concept analysis was conducted to determine the biotechnology concepts relevant to project activities, while task analysis was used to formulate learning activities that support students' creative thinking skills.

The second stage, Design stage, focuses on developing the e-module design, creating research instruments, and designing PjBL-based learning components. The e-module was designed as an interactive digital learning resource that integrated biotechnology concepts, Project-Based Learning (PjBL) activities, and Betawi local wisdom through a fermented product—*roti buaya*—which is relevant to biotechnology content. The e-module featured six core learning components arranged sequentially: BioQuestion, BioThink, BioPlan, BioAnalytic, BioReflection, and BioGallery. BioQuestion facilitated students' conceptual exploration and collaborative discussion. BioThink then introduced fundamental questions regarding the biotechnology concepts being studied to trigger the project workflow. BioPlan guided students in structuring and designing their project activities, while BioAnalytic supported the investigation process and data interpretation. BioReflection was utilized to encourage students' meta-cognitive thinking and assess their learning progress throughout the project. Finally, BioGallery provided a digital space for documenting and presenting their final project products.

Collectively, these components were intentionally structured to align with the PjBL syntax, thereby facilitating the development of creative thinking skills—specifically fluency, flexibility, originality, and elaboration.

The third stage is the Develop stage. This stage consisted of feasibility testing, practicality testing, and effectiveness testing. The feasibility testing was evaluated by three expert validators. The validators were selected based on their academic expertise and experience in biology education. All validators independently evaluated three aspects of the e-module: content, presentation, and language. After revision, practicality testing was conducted involving teachers and students. Teachers acted as observers who evaluated the implementation of biotechnology learning using the developed e-module. The observations focused on the implementation of learning activities, creative thinking skill development, and e-module usability and students' self-regulated learning. Students acted as users of the e-module and provided responses regarding the practicality of e-module. The effectiveness of the e-module was evaluated through the measurement of students' creative thinking skills before and after implementation. Students completed creative thinking tests consisting of indicators of fluency, flexibility, originality, and elaboration. The Disseminate stage involved the implementation and distribution of the revised e-module as a digital teaching resource.

The research subjects consisted of three experts acting as validators, two teachers as observers, and 69 eleventh-grade students from SMA Negeri 98 Jakarta. The participants were selected using purposive sampling with the following inclusion criteria: (1) students were enrolled in biology learning based on the Merdeka Curriculum, (2) students had studied relevant prerequisite concepts required for biotechnology learning, (3) students had not previously used the developed e-module, and (4) students participated in all learning activities and assessments. The implementation was conducted during biotechnology learning through project activities related to fermentation and product innovation using Betawi local wisdom contexts.

The instruments used in this study included an expert validation sheet, student response questionnaires, learning implementation observation sheets and creative thinking skill tests. The validity and practicality instruments—all measured using a five-point Likert scale—were analyzed using descriptive quantitative analysis by calculating their average scores and percentages using the following formula:

$$\text{Percentage } = \frac{\text{Score obtained}}{\text{Maximum Score}} \times 100\%$$

The percentages obtained are interpreted based on the criteria in Table 1.

Table 1. Category for the Validity and Practicality of the E-Module

Validity Precentage	Category
85–100%	Very Feasible/Practical
75–84%	Feasible /Practical
60–74%	Fairly Feasible /Practical
≤59%	Less Feasible /Practical

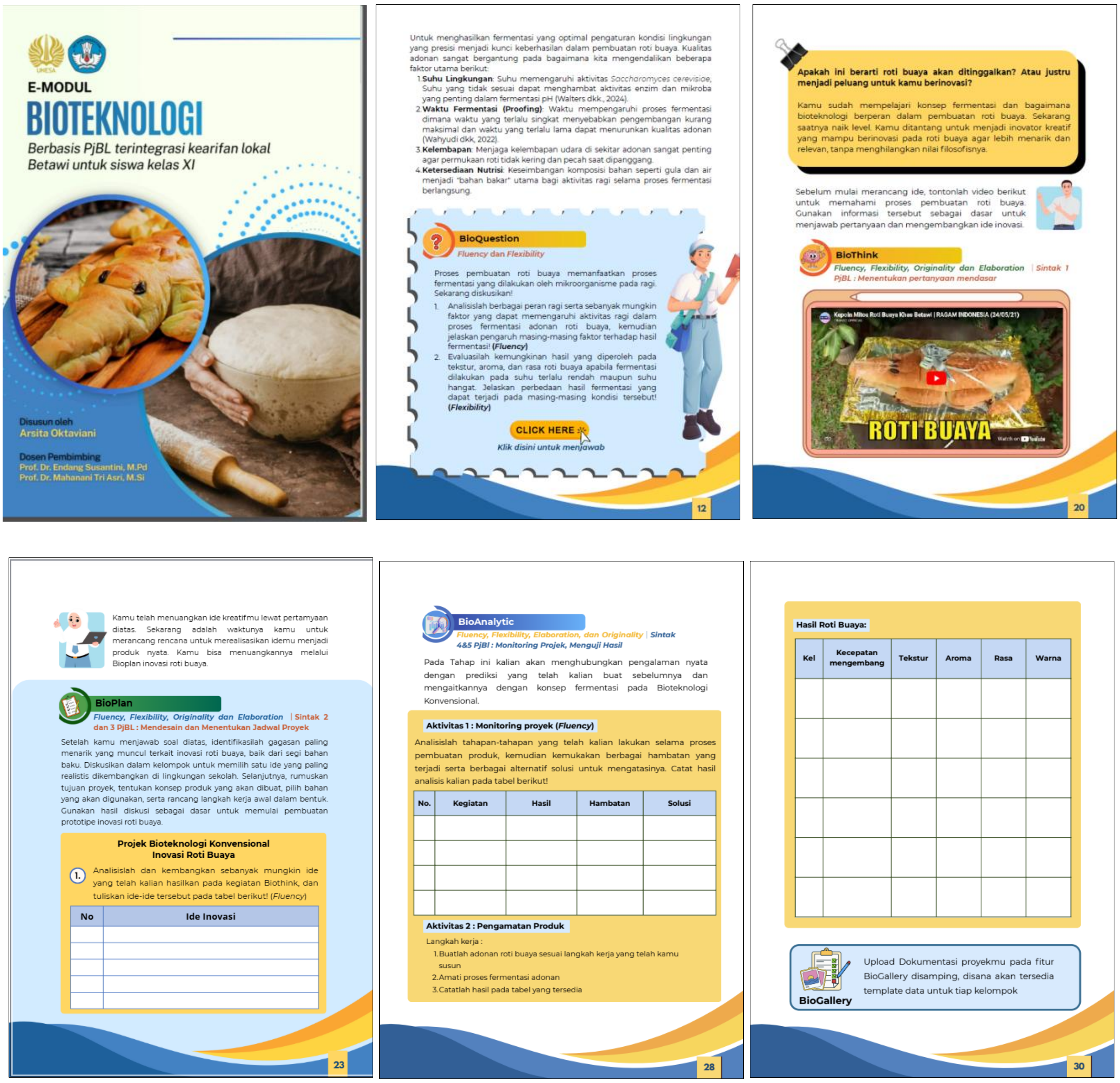
The creative thinking test consisted of essay questions developed based on Torrance's creative thinking indicators: fluency, flexibility, originality, and elaboration. The improvement of creative thinking skills was analyzed using normalized gain (N-gain). Normality and homogeneity tests were conducted before hypothesis testing, followed by paired-sample t-test analysis to examine differences between pretest and posttest scores.

RESULT AND DISCUSSION

Needs Analysis

Based on the results of research using the 4D development model, the needs analysis indicated that biotechnology learning activities were still predominantly focused on conceptual understanding through textbooks and teacher explanations. Learning activities that provided opportunities for students to generate ideas, design solutions, and develop biotechnology-based products were still limited. Therefore, an interactive e-module was developed to provide contextual and project-based learning experiences.

E-module serves as a flexible digital learning tool accessible on various devices through a single hyperlink. The e-module integrated biotechnology concepts, PjBL syntax, Betawi local wisdom, and creative thinking indicators (fluency, flexibility, originality, and elaboration). Betawi local wisdom was represented through *roti buaya*, which served as the contextual project in conventional biotechnology. The selection of *roti buaya* was based on its cultural significance in Betawi traditions and its relevance to fermentation processes, enabling students to connect scientific concepts with their surrounding cultural environment. The structure and main features of the developed e-module are presented in **Figure 1**.



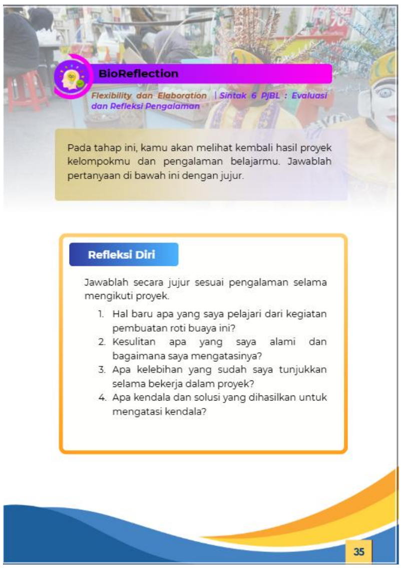


Figure 1. Interface and Main Features of the Developed Biotechnology E-Module (a) cover (b) BioQuestion (c) BioThink (d) BioAnalytic (e) BioGallery (f) BioReflection

Figure 1 presents the overview of the developed biotechnology e-module. The cover design represents the integration of biotechnology concepts and Betawi local wisdom, while the main features demonstrate the implementation of PjBL activities and creative thinking-oriented tasks. The developed e-module consisted of seven integrated features that supported the implementation of PjBL and the development of creative thinking skills (Figure 1). The relationship between each feature, the PjBL stages, and creative thinking indicators is summarized in Table 1.

Tabel 1. The relationship between each feature, the PjBL stages, and creative thinking indicators

E-Module Features	PjBL Syntax	Creative Thinking Indicator	Function
BioQuestion	Start with an Essential Question	Fluency dan Flexibility	Collaborative chat forum and Problem exploration
BioThink		Fluency, Flexibility, Originality, Elaboration	*Roti buaya* contextual multi-media case study to identify project idea
BioPlan	Design Project and Create Schedule	Fluency, Flexibility, Originality, Elaboration	Assist student in designing project plan and creating schedule
BioAnalytic	Monitor the Students and the Progress and Assess the Outcome	Fluency, Flexibility, Originality, Elaboration	Facilitates data analysis sheets and product improvement
BioGallery		Flexibility	Digital showcase of final student product innovations
BioReflection	Evaluate the Experience	Flexibility, Elaboration	Encourage students to reflect on learning and project outcomes

As shown in Table 1, each feature was intentionally designed to support specific stages of PjBL while simultaneously facilitating different dimensions of creative thinking. By embedding creative thinking indicators directly within the PjBL framework, this e-module empowers students to brainstorm novel ideas, assess alternative problem-solving strategies, polish their final project outputs, and effectively present their innovations. This deliberate synthesis serves as a key differentiating factor, distinguishing this digital resource from conventional biology e-modules that predominantly focus on rote content delivery rather than explicitly embedding creative cognitive pathways into learning tasks (Purnamasari et al., 2025).

The developed e-module also successfully integrates Betawi local wisdom, specifically *roti buaya*, into conventional biotechnology topics delivered through a contextual Project-Based Learning (PjBL) framework. This digital resource effectively bridges conceptual knowledge with practical execution by exploring the history, philosophy, and socio-economic values of *roti buaya* within the Betawi community, alongside a detailed scientific analysis of yeast (*Saccharomyces cerevisiae*) and the critical factors influencing fermentation. This conceptual foundation is then actualized through an authentic *roti buaya* innovation project structured around PjBL syntax. Under this pedagogical setup, students are motivated to integrate scientific principles with traditional practices while generating innovative product ideas, a process driven by the fact that integrating local wisdom into instruction effectively enhances higher-order thinking skills—specifically analytical, evaluative, and creative capabilities (Imron et al., 2026; Rosyidah et al., 2025b).

Expert Validation

Expert validation was conducted to evaluate the validity of e-module based on content, presentation, and language. The results of the expert validation are presented in Table 1.

Table 2. Validation Results of the PjBL-Based E-Module Integrated with Betawi Local Wisdom

Aspect	Mean Score	Validity Precentage	Category
Content	4.54	90.8	Very Valid
Presentation	4.72	94.4	Very Valid
Language	4.58	91.6	Very Valid
Average	4.60	92.4	Very Valid

Based on Table 1, e-module that has been developed was categorized as very valid based on the expert validation results in terms of content, presentation, and language. The presentation aspect obtained the highest score (92.4%) indicates that the e-module has an attractive and systematic appearance, supported by high-quality images, icons, and videos, as well as a consistent layout that enhances its visual appeal. A well-designed visual presentation plays an important role in attracting students' attention and increasing their interest in learning. Digital learning media that are visually appealing, interactive, and easy to use have been shown to improve students' engagement, motivation, and learning interest (Sari et al., 2024). The language aspect obtained a very valid category (91.6%), indicating that the language used in the e-module is clear and appropriate for the developmental level of high school students. The content aspect obtained the lowest score (90.8%) among the three aspects, although it remained within the "very valid" category. The validators suggested strengthening several conceptual explanations, particularly those related to biotechnology principles and the scientific basis of fermentation. These suggestions indicate that while the learning content was accurate and aligned with the curriculum, greater conceptual depth and stronger contextual integration would further improve the e-modul and ensure it does not lead to any scientific misconceptions (Sipayung & Purba, 2024). The validators also provided qualitative feedback to refine the product before implementation. The major comments and revisions are summarized in Table 3

Tabel 3. Summary of Validator Feedback and Revisions

Experts' Feedback / Suggestions	Revision Actions Taken (Pre- vs. Post-Revision)
Embedding creative-thinking indicators into feature descriptions.	Descriptions of the e-module features were updated to explicitly integrate creative-thinking indicators across all sections, moving beyond the initial draft which only highlighted them in *BioAnalytic*.

Incorporating modern biotechnology content.	The scope of the e-module was expanded from an exclusive focus on conventional methods to comprehensively include modern biotechnology concepts.
Correcting scientific concepts regarding fermentation.	The text was refined to clarify that CO_2 production involves both respiration and fermentation pathways (previously attributed solely to fermentation). Additionally, specific examples of relevant bacterial and mold species were added.
Upgrading the cognitive levels of module questions.	Low-level operational verbs targeting basic recall and understanding (C1–C2) were systematically replaced with higher-order items targeting application, analysis, evaluation, and creation (C3–C6).
Expanding the socio-cultural and economic contexts of *roti buaya*.	Content regarding *roti buaya* was enriched to comprehensively cover its philosophical, social, and economic dimensions, shifting from the baseline draft which only touched upon its basic cultural and technological aspects.

These formative revisions ensured that all conceptual ambiguities were eliminated and that the learning activities were robustly aligned with higher-order thinking metrics. Consequently, the refined e-module was deemed fully valid, scientifically accurate, and pedagogically sound, making it ready for field implementation to assess its practical impact on students' creative-thinking skills

Practicality of E-module

A field test was conducted to assess the practicality of the E-Module. Data on the practicality of the E-Module were obtained from students responses questionnaire of using the E-Module completed by students and from observation sheets filled out by teachers during the field trial phase, as detailed in Tables 4 and 5.

Table 4. Students' Responses to the Practicality of the E-Module

Aspect	Mean Score	Practicality Precentage	Category
Ease of Use	4.55	90.9	Very Practical
Clarity of Instructions and Appeal	4.59	91.9	Very Practical
Alignment with PjBL	4.53	90.7	Very Practical
Support for Creative Thinking	4.52	90.4	Very Practical
Benefits for Learning	4.62	92.3	Very Practical
Average	4.56	91.2	Very Practical

According to the results of student response questionnaire, the e-module received an an average practicality precentage of 91.24%, placing it in the very practical category. These results show that the e-module is easy to use, has clear instructions, can be accessed flexibly through digital devices, and supports the learning implementation process because it contains systematic activity steps and project guidelines. Consequently, the developed e-module is deemed highly feasible and suitable for implementation as an instructional material for biotechnology topics. This finding aligns with research by Rahayu & Balqis (2025), which asserts that high practicality scores indicate that an e-module is not only viable for classroom instruction but also capable of enhancing student engagement and learning motivation, thereby rendering the learning process more effective and contextualized against various real-world challenges.

Table 5. Observation of Instructional Implementation Feasibility

Aspect	Mean Score	Practicality Precentage	Category
instructional Implementation	4.80	96	Very Practical
Support for Creative Thinking	4.75	95	Very Practical
Ease of Use and Self-Regulated Learning	4.70	94	Very Practical

Average	4.75	95	Very Practical

Observational data revealed that the instructional implementation aspect achieved the highest evaluation under the very practical category. This indicates that the e-module effectively supports the planned Project-Based Learning (PjBL) syntax, enabling a systematic and directed learning process through its structured content and features. However, time allocation during project execution received the lowest score, as students required wider timeframes for product manufacturing and refinement. This variation stems from the distinct working paces and capacities of each student group, making the initial schedule tight (Syahlan et al., 2023). Nevertheless, the overall learning goals remained uncompromised, confirming that the e-module offers high execution feasibility and classroom efficiency, aligning with previous findings that PjBL-based modules robustly facilitate structured instructional delivery (Praptama et al., 2023)

Furthermore, the module's support for creative thinking was categorized as very practical, demonstrating that the embedded project tasks and open-ended prompts successfully fostered students' capacity to generate ideas, evaluate alternative solutions, and link biotechnology concepts to daily challenges (Torrance, 1974). Concurrently, the usability and independent learning aspect reached 94%, proving that the digital tool is highly accessible. The systematic interface and self-directed learning features successfully enhanced student autonomy and active participation (Praptama et al., 2023). Overall, the e-module achieved an average observational score of 91.5% (very practical). Consequently, the developed e-module is deemed practical for use as learning material for biotechnology topics

Effectiveness of E-module

The effectiveness of the developed biotechnology e-module was evaluated based on the improvement of students' creative thinking skills after participating in learning activities using the e-module. The effectiveness test was conducted using a pretest–posttest design, followed by N-gain analysis and inferential statistical tests. The descriptive results of students' creative thinking scores are presented in Table 6.

Table 5. Pretest, Posstest and N-gain Scores of Students' Creative Thinking (N=69)

Variable	Pretest	Posttest	N-gain	Category
Creative Thinking Skills	48	82	0,65	Moderate

The effectiveness of the developed biotechnology e-module was evaluated based on the improvement in students' creative thinking skills after the implementation of Project-Based Learning integrated with Betawi local wisdom. As presented in Table 6, students' creative thinking skills improved from the pretest to the posttest, resulting in an overall N-gain of 0.65, which falls within the moderate category. These results indicate that the developed e-module is effective in enhancing students' creative-thinking skills, yielding a moderate-category improvement. This gradual development is directly supported by the structured PjBL syntax, which systematically encourages students to brainstorm ideas, evaluate alternative solutions, develop innovation products, and engage in self-reflection. This finding aligns with Guo et al. (2020) who asserted that PjBL implementation robustly enhances creative-thinking capacities by actively engaging students in authentic problem-solving and project completion. These activities provided opportunities for students to practice the dimensions of creative thinking, including fluency, flexibility, originality, and elaboration. The improvement of each creative thinking indicator is presented in Figure 2.

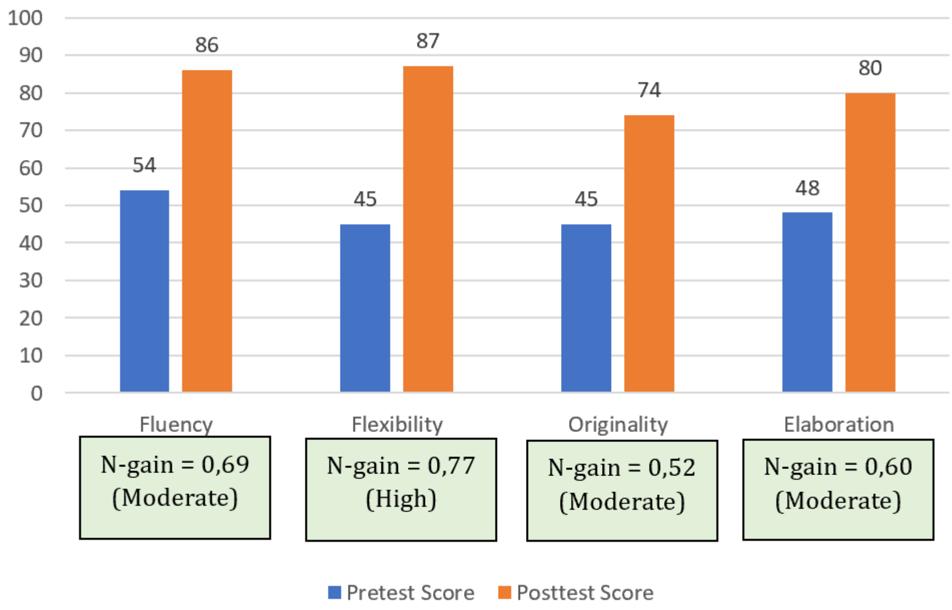


Figure 2. Pretest, Posttest, and N-gain of Creative Thinking Indicators

As shown in Figure 3, all creative thinking indicators improved after the implementation of the developed e-module. The differences among the indicators indicate that each dimension of creative thinking develops at a different rate. The highest N-Gain score in both classes was achieved by the *Flexibility* indicator with a value of 0.77, which falls into the high category. This demonstrates a major improvement in students' capacity to propose alternative solutions or diverse perspectives. For instance, when the bread fermentation progressed slowly, students adaptively relocated the dough outdoors to a warmer environment to accelerate proofing. Conversely, the *Originality* indicator yielded the lowest N-Gain score of 0.52, placing it in the moderate category and indicating that generating novel, unique, or uncommon ideas remains more challenging for students compared to other creative-thinking metrics. Although the developed e-module encouraged students to innovate through the *roti buaya* project, originality is considered one of the most complex dimensions of creative thinking, as it requires extensive exploration, evaluation, and refinement of ideas (OECD, 2024).

To determine the statistical significance of these improvements, a paired sample t-test was conducted after ensuring the data met normality via the Kolmogorov-Smirnov test and homogeneity via Levene's test. The paired sample t-test revealed a significance value (Sig. 2-tailed) of 0.000 ($p < 0.05$), confirming a significant difference between pretest and posttest scores. Consequently, these statistical outcomes prove that the utilization of the developed PjBL-based e-module integrated with Betawi local wisdom exerts a significant positive impact on enhancing high school students' creative-thinking skills in biotechnology.

The improvement in students' creative thinking skills may be attributed to the contextual and student-centered learning experiences provided by the e-module. The integration of biotechnology concepts with Betawi local wisdom through the *roti buaya* project enabled students to relate scientific knowledge to real-life cultural contexts, thereby fostering creative-thinking skills. This outcome aligns with findings by Ifrianti et al. (2025), which demonstrated that integrating local wisdom into Project-Based Learning (PjBL) significantly enhances students' creative capacities. Through active involvement in project workflows that yield tangible products, students are provided with ample space to explore ideas, develop innovations, and synthesize conceptual knowledge with local contexts to elevate final product quality which supported the development of fluency, flexibility, originality, and elaboration.

These findings have important implications for biology education. The developed e-module provides an alternative digital learning resource that supports the implementation of PjBL in biotechnology learning while promoting meaningful and contextual learning experiences. By integrating scientific concepts, project activities, and local cultural contexts, the e-module can help teachers facilitate student-centered learning and encourage students to apply biotechnology knowledge in authentic situations. The study also contributes to the development of digital learning materials by demonstrating how local wisdom can be integrated into biotechnology education to support higher-order thinking skills. The use of *roti buaya* as a contextual learning resource provides an example of how cultural products can be utilized as meaningful contexts for science learning rather than merely serving as additional information.

Despite these contributions, this study has several limitations. First, the implementation of this study was conducted in only one school and involved only one biology topic. Second, while the e-module successfully enhanced creative thinking skills, the average improvement fell within the moderate category. This suggests that while the e-module is effective, further pedagogical strategies are required to fully maximize students' creative potential. Therefore, future studies are recommended to investigate more intensive scaffolding techniques within the digital layout and expand the implementation scope across multiple schools and diverse biology topics to achieve higher competency levels and broader generalizability.

Discussion

The findings of this study demonstrate that the Project-Based Learning (PjBL)-based biotechnology e-module integrated with Betawi local wisdom is valid, practical, and effective in improving senior high school students' creative thinking skills. The expert validation results indicated that the e-module reached a very valid category, suggesting that its content, presentation, and language were sufficiently aligned with curriculum demands, scientific accuracy, and students' cognitive level. In addition, the practicality results from student responses and instructional implementation observations showed that the e-module was easy to use, visually accessible, and pedagogically supportive of project-based learning activities. The effectiveness test further confirmed that students' creative thinking skills increased from pretest to posttest, with an overall N-gain score of 0.65 in the moderate category. Among the four creative thinking indicators, flexibility showed the highest improvement, whereas originality demonstrated the lowest gain. These results indicate that the developed e-module was particularly effective in helping students generate alternative solutions and adapt their ideas during project completion, although producing highly novel ideas remained more challenging.

These findings are consistent with global research showing that PjBL can strengthen students' learning outcomes by engaging them in authentic inquiry, problem solving, collaboration, and product-oriented learning. Guo et al. (2020) reported that PjBL improves cognitive, affective, and behavioral learning outcomes because it allows students to work on meaningful tasks rather than passively receive information. In the present study, this mechanism was visible in the way students used the roti buaya project to connect fermentation concepts with cultural practices and product innovation. Similarly, OECD (2024) emphasized that creative thinking requires students to generate diverse, original, and useful ideas across different contexts. The higher gain in flexibility supports this view because students were able to propose different strategies and adjust their project plans when facing practical challenges during the fermentation process. However, the lower gain in originality also aligns with OECD's argument that originality is a more complex dimension of creativity, as it requires students not only to produce many ideas but also to move beyond conventional patterns of thinking.

The results also support recent international and national literature on digital learning materials and local-wisdom-based science education. Aliyah and Widiyatmoko (2023) found that biotechnology e-modules can improve students' critical and creative thinking skills when they are designed around meaningful and applied learning activities. The present study extends their findings by adding a culturally situated project context, namely roti buaya as a representation of Betawi local wisdom. In addition, Purnamasari et al. (2025) showed that PjBL-based e-modules integrated with local wisdom can enhance creative thinking in biology learning. The similarity between their findings and the present study suggests that local cultural objects can function not merely as contextual decoration but as pedagogical anchors that connect scientific concepts, social meaning, and creative product development. Nevertheless, the moderate N-gain in this study indicates that digital modules and local wisdom alone are not sufficient to maximize creativity; they must be accompanied by sustained scaffolding, repeated opportunities for ideation, and teacher facilitation that explicitly pushes students toward more original outcomes.

In the Indonesian context, the findings are particularly relevant because biology learning in many schools still tends to emphasize conceptual explanation and textbook-based understanding. The needs analysis in this study showed that biotechnology learning at the research site had not fully provided opportunities for students to design products, generate innovative ideas, and solve contextual problems. This condition is consistent with Fitri et al. (2024), who argued that PjBL is needed to cultivate creativity because it encourages students to investigate real problems and produce tangible solutions. Likewise, Rosyidah et al. (2025) emphasized that integrating local wisdom and STEM/science education can support meaningful learning and strengthen the connection between school science and students' socio-cultural environment. The use of roti buaya in this study therefore offers a locally grounded strategy for making biotechnology more concrete. Instead of teaching fermentation as an abstract biological process, the e-module situates it within a familiar cultural product, allowing students to understand yeast activity, product modification, and cultural value simultaneously.

The difference between flexibility and originality deserves critical interpretation. The high improvement in flexibility suggests that students were able to respond adaptively to project-based situations. This is understandable because PjBL exposes students to practical constraints, such as ingredient selection, fermentation time, product shape, and presentation, which naturally require alternative solutions. However, originality requires a higher level of creative risk-taking and conceptual independence. Students may still rely on familiar product ideas or imitate examples provided in the module, particularly if they have limited prior experience in designing biotechnology-based innovations. Therefore, the moderate gain in originality should not be interpreted as a weakness of the e-module alone but as evidence that originality requires longer learning cycles, richer exposure to examples, and more explicit creative scaffolding. This finding resonates with Wafiyah et al. (2025), who found that PjBL can improve creative thinking but still requires careful classroom support to ensure that students move beyond routine responses.

Theoretically, this study strengthens the argument that creative thinking develops more effectively when learning integrates cognitive, contextual, and productive dimensions. The findings support the PjBL framework, which assumes that students construct knowledge more deeply when they investigate authentic problems and produce meaningful artifacts. The integration of Betawi local wisdom also extends the theoretical understanding of contextual learning by showing that culture can serve as a bridge between scientific abstraction and creative application. In this sense, local wisdom does not merely support cultural preservation but also functions as a cognitive scaffold that helps students interpret scientific concepts through familiar social practices. Pedagogically, the study suggests that biology teachers should design digital learning materials that do not only present content but also guide students through inquiry, planning, product development, reflection, and presentation. Such an approach may improve student engagement because learners are positioned as active designers of knowledge rather than passive recipients of information.

From a broader educational perspective, the developed e-module also has implications for digital literacy, responsible online learning behavior, and students' learning autonomy. Although emotional well-being and online identity formation were not directly measured in this study, the use of structured digital learning spaces such as BioQuestion, BioPlan, BioAnalytic, BioGallery, and BioReflection may encourage students to communicate ideas, document learning processes, and present products more responsibly in digital environments. Policy-wise, the findings imply that schools and education authorities should support the development of culturally responsive digital learning resources, particularly for science subjects that require contextualization and experimentation. Policies on digital learning should not focus only on device provision or platform adoption but also on the quality of instructional design, teacher capacity, student creativity, and the integration of local cultural knowledge. In addition, mental health and digital behavior policies in schools should encourage constructive digital interaction, collaborative online learning, and safe feedback practices, especially when students are required to present their work in digital galleries or learning platforms.

The novelty of this study lies in the integration of three components that are often developed separately: PjBL, biotechnology e-modules, and Betawi local wisdom. Previous studies have examined PjBL-based e-modules, local-wisdom-based science learning, or biotechnology instructional materials, but this study combines them into a single digital instructional design focused specifically on creative thinking skills. The use of roti buaya as a biotechnology project context is also a distinctive contribution because it transforms a cultural product into a scientific and pedagogical object. This approach expands the literature on culturally responsive science education by demonstrating how local food traditions can be used to teach fermentation, product innovation, and creative problem solving. Methodologically, the study contributes by using a systematic 4D development model, expert validation, practicality testing, and pretest–posttest effectiveness analysis, thereby providing a comprehensive basis for judging the quality of the developed e-module.

Despite these contributions, this study has several limitations. First, the implementation was conducted in only one school and involved 69 eleventh-grade students, which may limit the generalizability of the findings to other regions, school types, or student populations. Second, the study focused only on biotechnology, so the effectiveness of this model in other biology topics remains uncertain. Third, although the N-gain analysis and paired-sample t-test confirmed improvement in creative thinking, the study did not include a control group, making it difficult to isolate the effect of the e-module from other classroom factors. Fourth, originality remained in the moderate category, indicating that the e-module still requires stronger scaffolding to help students produce more unique and uncommon ideas. Future research should therefore test the e-module across multiple schools, compare it with conventional or non-local-wisdom-based digital modules, examine long-term retention of creative thinking skills, and explore how teacher facilitation, peer collaboration, emotional engagement, and digital media literacy influence students' creative performance in project-based biotechnology learning.

CONCLUSION

Based on the results of the research and development process, it is concluded that the PjBL-based biology e-module integrated with Betawi local wisdom was successfully developed utilizing the 4D model to establish a highly contextual learning environment through the local wisdom of *roti buaya.* The digital resource achieved exceptional validity with an average expert evaluation score of 92%, confirming its status as highly valid and feasible for classroom implementation. Furthermore, evaluation data from student responses and learning implementation observations demonstrated that the e-module is highly practical, accessible, and supportive of project-based pedagogy. Lastly, the e-module proved effective in systematically enhancing students' creative-thinking skills, as evidenced by an average overall N-Gain score of 0.65, which falls into the moderate category, alongside improvements across specific creativity indicators ranging from moderate to high. This positive shift is statistically supported by a paired sample t-test significance value of less than the alpha level of 0.05, thereby validating that the developed e-module exerts a significant positive impact on fostering high school students' creative thinking skill in biotechnology. The integration of PjBL syntax, Betawi local wisdom, and indicators of creative thinking makes the e-module a contextual teaching material to enhance students' creative thinking skills. Therefore, the developed e-module can be used as an alternative digital teaching material in biotechnology education at the high school level.

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