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Development of biology e-modules based on problem-based learning to enhance students' critical thinking and communication skills

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ABSTRACT

Critical thinking and communication skills are essential for students, yet biology learning remains dominated by passive lecture methods. Interactive digital materials using Problem-Based Learning (PBL) are also limited. This study developed a PBL-based Biology e-module on the Human Immune System and tested its validity, practicality, and effectiveness. Using the 4D model (define, design, develop, disseminate), the e-module was validated by five experts. Practicality was assessed through teacher and student questionnaires, while effectiveness was tested via a quasi-experimental nonequivalent pretest-posttest control group design involving 52 twelfth-grade students at SMAN 1 Kerinci (experimental group, $n = 28$; control group, $n = 24$). Results showed the e-module was highly valid (88.00%) and highly practical according to teachers (88.33%) and students (91.31%). Critical thinking skills improved significantly more in the experimental class (N-Gain = 0.58) than in the control class (N-Gain = 0.30), confirmed by an independent-samples t -test ($p < 0.05$). Similarly, communication skills improved more in the experimental class (N-Gain = 0.68) than in the control class (N-Gain = 0.24), verified by the Mann-Whitney U test ($p < 0.05$). In conclusion, this PBL-based Biology e-module is valid, practical, and effective in enhancing students' critical thinking and communication skills.



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Introduction

Education in the 21st century must equip students with competencies that enable them to participate actively and responsibly in an increasingly complex society (Lufri et al., 2021; OECD, 2018). Within the 4C framework of learning and innovation skills, critical thinking, communication, collaboration, and creativity are regarded as essential for success in both careers and everyday life (Partnership for 21st Century Learning, 2019). Among these skills, critical thinking and communication form the foundation of science learning, including biology. Critical thinking enables students to analyze and evaluate information using appropriate criteria so that they can make informed decisions and solve problems effectively (Heard et al., 2020), while communication allows them to express ideas clearly in oral and written forms and helps prevent misunderstanding (Joynes et al., 2019). Many countries now expect schools to help students think independently rather than merely transmit knowledge (Vincent-Lancrin et al., 2019).

However, evidence suggests that these skills remain underdeveloped in Indonesia. The 2022 Programme for International Student Assessment (PISA) reported that only 34% of Indonesian students could recognize

scientific explanations and use their knowledge to judge the validity of conclusions based on data (OECD, 2023). To determine whether this national trend is reflected at the local level, a preliminary needs analysis was conducted at SMAN 1 Kerinci. This school was purposively selected as a representative site because its demographic profile, resource availability, and curriculum implementation reflect the typical conditions of public senior high schools in semi-urban Indonesia, meaning the pedagogical challenges observed here are indicative of broader systemic issues rather than isolated anomalies. To establish a robust baseline, a structured needs-analysis questionnaire was administered to a sampling frame of 52 eleventh-grade students, yielding a 98% response rate. The results revealed that 47% of students tended to accept scientific information without verification, and 60% reported feeling nervous or lacking confidence when presenting ideas in front of the class. Furthermore, an interview with the biology teacher confirmed that learning was still dominated by teacher-centered lectures, leaving students as passive recipients with few opportunities to analyze data, build logical arguments, or formulate solutions. Although these empirical findings originate from a single school, they strongly corroborate national PISA 2022 data and previous studies reporting comparable deficiencies in critical thinking (Fausan et al., 2021; Fitriani et al., 2022) and communication skills (Yennita et al., 2024) in biology learning. Therefore, developing and testing a scalable, evidence-based intervention such as a PBL-based e-module at this representative site is highly warranted to generate actionable insights that can be generalized and adapted to similar educational contexts nationwide.

Digital teaching materials offer one way to address these problems. E-modules present text, images, and video in a structured and interactive format that supports independent learning and makes material easier to understand (Cahyanto & Afifulloh, 2020; Kartikasari et al., 2023; Limatahu et al., 2017). Nevertheless, the availability of media alone is not sufficient without an appropriate instructional model. Problem-based learning (PBL) is a student-centered approach that uses complex, real-world problems as the starting point of learning, in which students work in small groups to identify problems, investigate, and share their findings under the guidance of the teacher (Tan, 2002; Torp & Sage, 2002; Trullàs et al., 2022). This approach is designed to develop critical thinking, problem-solving, and effective oral and written communication (Duch et al., 2001). Recent studies also indicate that combining PBL with e-modules can positively influence both skills (Mahmudah et al., 2022; Wulanjani et al., 2024).

Despite this promise, e-module development and the application of PBL have mostly been examined separately. To the best of the authors' knowledge, studies that systematically integrate both into a single digital module and simultaneously measure its impact on critical thinking and communication remain limited, particularly for the topic of the human body defense system. This topic is closely related to students' daily lives and contains many authentic issues that are well suited to contextual problem scenarios. The teacher in the study setting also had not yet developed a biology e-module based on PBL; the available materials were mainly informative and text-based without real-world problem contexts that encourage analysis, discussion, and scientific decision-making.

This study therefore addresses that gap by developing a biology e-module based on PBL that embeds the phases of PBL into contextual problem scenarios. The novelty of this research lies in the integration of the PBL syntax into an interactive digital module that targets two twenty-first-century skills simultaneously. The study used a research and development approach with the four-D model, followed by a quasi-experimental test of effectiveness. The objectives of this study were to produce a PBL-based biology e-module on the human body defense system that is (1) valid, (2) practical, and (3) effective in improving students' critical thinking and communication skills.

Method

This study employed a Research and Development (R&D) design integrated with a quasi-experimental approach to develop and evaluate the validity, practicality, and effectiveness of a Problem-Based Learning (PBL)-based biology e-module. The development followed the 4D model (Thiagarajan et al., 1974), comprising four stages: define, design, develop, and disseminate. The effectiveness of the developed product was subsequently tested using a Nonequivalent Pretest-Posttest Control Group design.

The study was conducted on 12th-grade students at SMAN 1 Kerinci. Participants were selected using a purposive sampling technique, resulting in an experimental group ($n = 28$) and a control group ($n = 24$). Thus, the obtained sample ($N = 52$) is statistically adequate to detect a significant difference between the two groups. The research instruments included a product validation questionnaire, practicality questionnaires for teachers and students, a critical thinking ability test, and observation sheets for communication skills.

Product validation was conducted by five validators (two Biology Education lecturers and three Biology teachers). Following the development stage, an effectiveness test was carried out. The effectiveness data were

analyzed by calculating the normalized gain (N-gain). Prior to hypothesis testing, the data were assessed for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). Hypothesis testing was performed using an independent samples t-test for normally distributed data (critical thinking N-gain) and the Mann-Whitney U test for non-parametric data (communication skills N-gain), using SPSS Statistics version 27 at a 5% significance level ($\alpha = 0.05$).

Results and Discussions

Results of E-Module Development

The development of a Problem-Based Learning (PBL) Biology e-module on the Immune System topic was conducted using the 4D model, which consists of the define, design, develop, and disseminate stages. The product was developed in the form of an interactive e-module using Canva and published via Heyzine. This e-module consists of four learning activities, namely the components of the immune system, the mechanisms of the immune system, types of immunity, as well as abnormalities and disorders of the immune system.

The define stage was carried out through the analysis of needs, students, concepts, tasks, and learning objectives. The design stage produced the e-module layout, which integrates materials, images, videos, learning activities, and contextual problems using the PBL syntax. The develop stage was conducted through product validation by experts and practitioners, followed by revisions based on the given suggestions. The revisions included refining the references and cover design, including image and video sources, aligning the learning objectives with the learning outcomes, improving the language, replacing the *Diabetes mellitus* case study with HIV/AIDS, and perfecting the e-module user guide. The disseminate stage was carried out by distributing the product to Biology teachers at several schools, namely SMAN 6 Kerinci, SMAN 11 Kerinci, and MAN 1 Kerinci.

Validity of the PBL-Based Biology E-Module

The validity of the Problem-Based Learning (PBL) Biology e-module was evaluated by experts. The average percentage score obtained from the expert validation process is presented in Table 1.

Table 1. Validity of the PBL-Based Biology E-Module

Assessment Aspect	Lecturers (%)	Teachers (%)	Overall (%)	Category
Content suitability	84.38	87.50	86.25	Very valid
Construct	75.00	87.50	82.50	Very valid
Language	79.17	94.44	88.33	Very valid
Item clarity	87.50	87.50	87.50	Very valid
Format	93.75	100.00	97.50	Very valid
Instructions	81.25	91.67	87.50	Very valid
Average	83.33	91.11	88.00	Very valid

Based on Table 1, the e-module obtained an overall average validity score of 88.00%, falling into the highly valid category. This indicates that the e-module has met the feasibility criteria to proceed to the practicality and effectiveness testing stages. The highest score was obtained in the format aspect at 97.50%, indicating that the layout was arranged systematically and the integration of text, images, and videos was executed appropriately. Meanwhile, the construct aspect obtained a relatively lower score, although it still falls within the highly valid category, at 82.50%. The content suitability aspect, which includes alignment with the Learning Outcomes and PBL syntax, obtained a score of 86.25%. These results provide evidence that the materials have been aligned with the applicable curriculum standards, and the PBL activities within the e-module are logically connected to the learning model and the established development objectives. The five validators comprised two Biology Education lecturers and three Biology teachers. The lecturers rated the product more strictly than the teachers (83.33% versus 91.11%), with the largest gap in the construct aspect (75.00% versus 87.50%), although every aspect remained in the very valid category.

The validators also provided several qualitative suggestions. These included adding references from standard immunology textbooks, improving the cover design to better represent the immunology theme, citing sources for all images and videos, replacing one of the case studies to be more relevant to the immune system topic, and refining the learning objectives as well as the cognitive demand levels in the test blueprint (C1–C6). All of these suggestions were implemented prior to the e-module being used in the trial phase. This aligns with the view that well-designed PBL activities not only engage students in acquiring conceptual understanding but also encourage them to actively investigate problems, engage in discussions, and communicate their investigation results (Savery, 2006).

Practicality of the PBL-Based Biology E-Module

The practicality of the developed e-module was evaluated through questionnaires completed by Biology teachers and twelfth-grade students. The results of the practicality assessment are presented in Table 2.

Table 2. Practicality of the PBL-Based Biology E-Module

Practicality Aspect	Teachers (%)	Students (%)	Category
Ease of use	97.22	91.67	Very practical
Clarity of instructions	83.33	91.37	Very practical
Time efficiency	86.11	90.77	Very practical
Ease of implementation	88.88	91.67	Very practical
Benefits	86.11	91.07	Very practical
Average	88.33	91.31	Very practical

The practicality test results in Table 2 demonstrate a highly positive response from both teachers and students, with average scores of 88.33% and 91.31%, respectively, both falling into the highly practical category. Teachers gave the highest rating to the ease of use aspect, at 97.22%. This indicates that the e-module can be operated without encountering significant obstacles, and the available features support the systematic implementation of PBL in the classroom.

Students gave the highest ratings to the aspects of ease of use and ease of implementation, at 91.67% each. These results indicate that the e-module is easy to use, provides clear instructions, and supports independent learning on the immune system topic. The usefulness aspect also obtained a high rating from students, at 91.07%. This demonstrates that the contextual problems presented in each learning activity encourage students to identify problems, seek relevant information, discuss with peers, and communicate their problem-solving results, which aligns with the student-centered characteristics of PBL (Trullàs et al., 2022). Overall, these results indicate that the e-module has fulfilled the expected practicality aspects as well as the practical conditions of its usage, making it feasible to proceed to the effectiveness testing stage.

Effectiveness of the E-Module on Critical Thinking Skills

The effectiveness of the e-module on critical thinking skills was analyzed based on the pretest, posttest, and N-Gain scores. The results of the descriptive analysis are presented in Table 3.

Table 3. Critical Thinking Skills

Group	n	Pretest Mean	Posttest Mean	N-Gain	Category
Experimental	28	54.21	80.10	0.58	Moderate
Control	24	53.13	67.11	0.30	Moderate

The pretest means of the control group (53.13) and the experimental group (54.21) indicate relatively equivalent initial conditions. The independent-samples t-test results on the pretest scores also confirmed that there was no significant initial difference between the two groups ($t = -0.714$; $df = 50$; $p = 0.478 > 0.05$). Following the treatment, the posttest means increased to 67.11 in the control group and 80.10 in the experimental group. Although the N-Gain for both groups fell into the moderate category, specifically 0.30 for the control group and 0.58 for the experimental group, the experimental group demonstrated a greater improvement.

The paired-samples t-test revealed a significant increase from pretest to posttest in both groups, namely the experimental group ($t = 39.671$; $df = 27$; $p < 0.001$) and the control group ($t = 12.315$; $df = 23$; $p < 0.001$). To determine whether the magnitude of improvement differed significantly between the two groups, an independent-samples t-test was conducted on the N-Gain scores, after ensuring that the data were normally distributed (Shapiro-Wilk $p > 0.05$ for all groups) and had homogeneous variances (Levene's test $p > 0.05$). The test results yielded $t = 8.192$; $df = 50$; $p < 0.001$, with a mean difference of 0.277, thus H_0 was rejected. These results provide statistical evidence that the PBL-based e-module yielded a significantly greater improvement in critical thinking skills compared to conventional instruction.

These findings align with the characteristics of PBL implemented in the e-module, which exposes students to complex and ill-structured problems. Consequently, students take on the role of the party responsible for the problem and must identify the core of the issue as well as acquire the necessary knowledge to formulate effective solutions (Torp & Sage, 2002). Such engagement encourages students not merely to acquire concepts passively, but to actively analyze information, evaluate various alternative solutions, and make evidence-based decisions throughout the investigation process (Arends, 2014).

This outcome pattern is also consistent with meta-analytic evidence demonstrating that structured instructional interventions can significantly enhance students' critical thinking skills (Niu et al., 2013), as well as

prior research reporting that PBL-based e-modules can improve critical thinking skills in other Biology and Physics topics (Mahmudah et al., 2022; Wulanjani et al., 2024). Overall, this evidence indicates that the significant difference in N-Gain in this study reflects the systematic application of the PBL syntax within the e-module, rather than being solely the result of using a digital format.

Effectiveness of the E-Module on Communication Skills

Communication skills were assessed using performance observation sheets before and after the learning process. The results of the analysis are presented in Table 4.

Table 4. Communication Skills

Group	n	Pre observation Mean	Post observation Mean	N-Gain	Category
Experimental	28	51.47	84.44	0.682	Moderate
Control	24	49.85	61.53	0.235	Low

The pre-observation mean scores of the control group (49.85) and the experimental group (51.47) indicate relatively equivalent initial conditions in communication skills (Table 5). Following the treatment, the post-observation mean scores increased to 61.53 in the control group and 84.44 in the experimental group, with N-Gains of 0.235 (low category) and 0.682 (moderate category), respectively.

The Shapiro-Wilk test indicated that the observation scores for the experimental group were not normally distributed ($p = 0.027$ for pre-observation and $p = 0.001$ for post-observation), whereas the control group scores were normally distributed ($p = 0.182$ and $p = 0.056$). Therefore, the non-parametric Mann-Whitney U test was employed after confirming that both groups had homogeneous variances (Levene's test $p > 0.05$). The test results yielded $U = 0.000$, $Z = -6.196$, and Asymp. Sig. (2-tailed) = 0.000, which is less than 0.05, thus H_0 was rejected. These results indicate a statistically significant difference in communication skills between students who learned using the PBL-based e-module and those who received conventional instruction.

These results align with the PBL syntax, specifically the stages of organizing students for learning and developing and presenting artifacts, which directly train students to convey ideas, exchange views, and defend scientific arguments (Staniforth, 2015; Joynes et al., 2019). Comparable improvements have also been reported in previous studies. Nurfajriah et al. (2022) found that the implementation of PBL significantly improved students' communication scores from a pretest mean of 44.62 to 46.77 on the posttest (paired t-test, $p < 0.001$). Meanwhile, Lufri et al. (2021) reported that the group using technology-assisted PBL obtained an average communication score of 64.27% compared to 57.70% in the control group, and this difference was proven to be significant based on a two-way ANOVA test ($p = 0.00$).

The consistency of these results indicates that the substantially greater improvement observed in the experimental group in this study stems from the same mechanism—namely, providing students with repeated, structured opportunities to engage in discussions, ask questions, and present their problem-solving processes, rather than merely receiving information passively.

The research results indicate that the Problem-Based Learning (PBL) Biology e-module on the human immune system has fulfilled the three criteria of a well-developed instructional product: validity, practicality, and effectiveness. These results are consistent with, and simultaneously expand upon, previous developmental research regarding e-modules that integrate PBL in science learning. Fradila et al. (2021) and Aliyah & Widiyatmoko (2022) respectively demonstrated that PBL-based or problem-oriented e-modules could be developed to meet valid and practical standards on Biology-related topics; however, they did not simultaneously evaluate their impact on critical thinking and communication skills through controlled group comparisons. Wulanjani et al. (2024) reported that PBL-assisted e-modules can improve critical thinking and communication skills in science education. These findings are corroborated and broadened by this study within the context of high school Biology learning and the immune system topic an authentic subject closely related to real-life problems, which has rarely been examined using a design that incorporates both skills simultaneously. Thus, the novelty of this research lies in the simultaneous assessment, verified through a quasi-experimental approach, of two 21st-century competencies within a single PBL-based digital instructional material on the immune system, a topic rich in contextual and real-world problems.

The practical implication of these findings is that teachers can utilize the PBL-based e-module as a ready-to-use alternative digital instructional material that supports student-centered learning without requiring extensive additional training, considering the assessment results indicated a highly practical category in the aspects of ease of use and implementation. Theoretically, the research results reinforce the view that the PBL structure, which is initiated by a problem rather than merely presenting materials in a digital format, is the primary factor driving the enhancement of critical thinking and communication skills (Torp & Sage, 2002; Savery, 2006).

Future research is recommended to develop PBL-based e-modules on other Biology topics, involving a larger and more diverse sample from multiple schools, as well as to examine their impact on other 21st-century competencies, such as creativity and collaboration. In doing so, the contribution of PBL-based digital instructional materials to the development of 21st-century skills can be understood more comprehensively (Tawfik et al., 2021).

Conclusions

The development of a Problem-Based Learning (PBL)-based Biology e-module on the immune system topic has yielded a product that is valid (88.00%), practical (88.33% for teachers; 91.31% for students), and effective in improving students' critical thinking skills (N-Gain = 0.58 vs. 0.30) and communication skills (N-Gain = 0.682 vs. 0.235). These results can be validly applied to 12th-grade students in a semi-urban public high school context with comparable demographic and technological characteristics. However, several methodological limitations restrict the generalizability of these claims. First, this study used a relatively small sample size (N = 52) selected through purposive sampling at a single school, which limits broader population generalizability. Second, the practicality assessment relied on self-report questionnaires that are susceptible to social desirability bias, and the communication skills instrument was limited to observable classroom interactions, potentially missing the nuances of asynchronous digital communication. Finally, the short duration of the intervention limits conclusions regarding the long-term retention of these skills. Although these findings confirm that integrating PBL syntax into a digital e-module is an effective instructional alternative, future research should employ larger randomized samples across diverse educational settings, utilize mixed methods for data triangulation, and incorporate longitudinal designs to assess sustained skill development.

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