



## Development of Interactive E-Modules Based on Problem-Based Learning (PBL) to Improve Students' Problem-Solving Skills in Biotechnology Materials

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Received: October 2025; Revised: December 2025; Published: January 2026

### Abstract

This study developed and evaluated a Problem-Based Learning (PBL)-based interactive e-module for biotechnology instruction, with a focus on improving students' problem-solving skills. The module was designed around contextual biotechnology issues related to industry and health to support students in connecting biological concepts with real-world applications. The study employed a Research and Development approach using the 4D model (Define, Design, Develop, Disseminate). Participants consisted of 15 Grade XII science students in a small-scale trial and 30 Grade XII science students in a large-scale implementation. Feasibility results indicated that the e-module met "good" criteria based on expert and practitioner appraisal: material expert (76.67%), media expert (76.56%), biology teacher (75.00%), and peer reviewers (76.11%). Practicality results from the small-scale trial showed positive student responses, including usability (80.8%; good), display and presentation (81.0%; excellent), and material presentation (79.4%; good). Effectiveness findings showed a moderate improvement in problem-solving performance in the small-scale trial (N-gain = 0.46). In the large-scale implementation, paired-samples analysis indicated a significant difference between students' performance before and after learning with the e-module ( $p = 0.029$ ), suggesting improved outcomes following implementation. Overall, the findings support that the PBL-based interactive e-module is feasible, practical, and associated with improved student problem-solving performance in biotechnology learning.

**Keywords:** interactive e-module; Problem-Based Learning; problem-solving skills; biotechnology

**How to Cite:** Mahariyanti, E., & Irwansah. (2026). Development of Interactive E-Modules Based on Problem-Based Learning (PBL) to Improve Students' Problem-Solving Skills in Biotechnology Materials. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, 14(1), 335–349. <https://doi.org/10.33394/j-ps.v14i1.18116>



<https://doi.org/10.33394/j-ps.v14i1.18116>

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## INTRODUCTION

Biology education plays a strategic role in preparing students to deal with complex real-world challenges that increasingly require evidence-based reasoning, critical thinking, and problem-solving competence (Fowler et al., 2024). These competencies are not only demanded by curriculum standards but are also essential for navigating rapid advances in science and technology that continuously reshape how knowledge is produced, applied, and evaluated (Beer et al., 2021; Rajsiglova et al., 2024; Mendez et al., 2024). Within biology, biotechnology is among the most conceptually demanding and context-dependent topics. It integrates microbiology, genetics, biochemistry, and technological applications, while simultaneously requiring students to interpret ethical, social, and industrial implications. Students are expected to move beyond memorizing definitions (e.g., fermentation, recombinant DNA) and instead interpret biotechnology as a set of tools used to solve problems in food processing, health innovation, environmental remediation, and industrial production (Martin et al., 2021; Renneberg, 2023). Consequently, biotechnology learning should be designed to help students

connect abstract concepts with authentic contexts, analyze constraints, evaluate alternative solutions, and justify decisions—abilities that are central to problem-solving (Moo, 2019).

Problem-Based Learning (PBL) has been widely recommended as an instructional approach to support these learning demands because it organizes learning around meaningful problems that require inquiry, reasoning, collaboration, and reflection. Empirical studies report that PBL can strengthen conceptual understanding and promote active engagement in science learning (Supiandi et al., 2016; Ramadhan, 2021; Anggraeni et al., 2023; Ali, 2019; Wahida et al., 2024). In biology education, PBL is particularly relevant because biological phenomena are often probabilistic, multi-causal, and embedded in real-world systems—conditions that naturally fit problem scenarios rather than linear lectures. Nevertheless, successful PBL implementation is not automatic. Teachers frequently report difficulties in designing high-quality problems, managing inquiry activities within time constraints, and providing scaffolding that supports students without reducing cognitive demand. Importantly, limitations in supportive learning media and insufficient teacher readiness to design and facilitate problem-oriented scenarios remain major barriers (Fidan & Tuncel, 2019). As a result, PBL is sometimes implemented superficially—reduced to “discussion after explanation”—and fails to deliver its intended benefits for higher-order thinking, particularly problem-solving.

These challenges are not only theoretical but also evident in school practice. At NW Suralaga High School, initial observations indicated that biotechnology instruction tended to remain teacher-centered and passive: teachers delivered content through lectures, while students received information with limited opportunities for exploration, argumentation, or application. This condition is further compounded by limited access to training or technical guidance on digital interactive learning media, which reduces teachers' capacity to design learning experiences that are both contextual and inquiry-oriented. In such situations, students often struggle to understand complex biotechnology concepts and have difficulty connecting classroom knowledge to daily life applications. Boredom and low learning motivation emerge when learning resources are not interactive and do not provide meaningful contexts that stimulate reasoning and decision-making (Mahariyanti, 2020). Ultimately, these conditions hinder the development of problem-solving skills and reduce the likelihood that biotechnology learning will be perceived as relevant and usable beyond school.

Interactive e-modules have been proposed as one practical solution to strengthen PBL implementation, especially when conventional resources and laboratory infrastructure are limited. E-modules can integrate text, images, animations, video, and interactive tasks that support self-paced learning, provide scaffolding, and guide students through inquiry steps. Several studies suggest that digital learning resources—when designed with clear pedagogy—can increase learning engagement and learning independence, and can support PBL by providing structured problems, guiding questions, and feedback mechanisms (Astalini et al., 2019; Komikesari et al., 2020). In biology learning, e-modules also offer opportunities to visualize abstract processes (e.g., gene expression, microbial growth kinetics) and provide contextual cases that are difficult to reproduce in school laboratories. Accordingly, PBL-based interactive e-modules are often positioned as tools that combine technological affordances with problem-oriented pedagogy (Adawiyah & Anwar, 2021; Trilestari & Almunawaroh, 2020; Kusumasaria et al., 2022; Rohmatulloh et al., 2023; Sartika et al., 2024).

However, despite a growing body of work on PBL and digital modules, the current literature and school practice reveal several important gaps that justify the present study. First, many development studies evaluate “validity–practicality–effectiveness” in a general sense but do not sufficiently specify how module features are aligned with each PBL phase (problem orientation, inquiry planning, investigation, solution development, and reflection). As a result, the pedagogical mechanism by which the module is expected to enhance problem-solving remains under-articulated, and replication becomes difficult. Second, many studies report learning gains without fully clarifying the operational definition of problem-solving skills or

providing detailed scoring rubrics and evidence of instrument validity and reliability. Without transparent indicators and scoring procedures, claims about improvement in problem-solving are difficult to verify and compare across studies. Third, biotechnology-specific PBL resources are still limited in many school contexts, particularly resources that explicitly use cases from industry and health (e.g., fermentation production chains, food safety biotechnology, diagnostic biotechnology) that match students' lived realities and regional needs. Biotechnology is often taught as "concept lists" rather than as a context-rich field of problem solving and innovation (Martin et al., 2021; Renneberg, 2023). These gaps are critical because they weaken both the scientific contribution (unclear mechanism and measurement) and the practical contribution (limited contextual relevance and implementation guidance) of learning media development studies.

Based on these gaps, the novelty of this study is positioned in three interrelated contributions. First, this research develops a PBL-based interactive e-module specifically for biotechnology that systematically embeds authentic problems grounded in industry and health contexts, enabling students to connect biological concepts to real applications and constraints. Second, the module is designed with explicit alignment between interactive features (case triggers, guiding questions, investigation tasks, reflective prompts, and feedback) and the phases of PBL, so that the learning mechanism is clear, instructional decisions are defensible, and the product can be replicated or adapted in other contexts. Third, the study emphasizes a transparent and indicator-based assessment of students' problem-solving skills, defining problem-solving as a sequence of competencies such as problem identification, information gathering, solution planning, implementation reasoning, and evaluation/reflection. This explicit operationalization is intended to strengthen the credibility of effectiveness claims and provide a clearer basis for future comparative studies.

To address both scientific and classroom needs, this research aims to: (1) develop a PBL-based interactive e-module on biotechnology using a systematic development model; (2) evaluate the quality of the developed e-module in terms of validity (content and design appropriateness), practicality (ease of use and user response), and effectiveness (learning outcomes related to problem-solving skills); and (3) analyze whether the implementation of the e-module supports improvement in students' biotechnology problem-solving skills. These objectives are not merely procedural (develop-test-report), but are tied to the broader goal of strengthening biotechnology instruction so that it becomes context-rich, inquiry-driven, and skill-oriented. In this study, the scope of effectiveness is focused on problem-solving outcomes in the biotechnology topic among the participating students, while acknowledging that broader generalization requires further testing across schools, grade levels, and varied infrastructure conditions.

This research is urgent for at least two reasons. From an educational innovation perspective, it responds to the increasing need for learning resources that are adaptive to digital development and that can scaffold higher-order thinking, especially in schools where laboratory resources and teacher training are limited. From a scientific perspective, it seeks to contribute more than a routine development report by clarifying the gap, articulating a pedagogical mechanism (feature-PBL alignment), and strengthening the transparency of problem-solving assessment—elements that are frequently underdeveloped in similar studies. Ultimately, by integrating PBL principles with interactive e-module design, this study is expected to provide a feasible and contextually relevant learning resource that supports student engagement and helps students practice solving biotechnology problems in ways that resemble how biotechnology is applied in real life.

In summary, persistent challenges in biotechnology learning—conceptual complexity, limited contextualization, teacher-centered practices, and insufficient interactive media—reflect the need for a structured solution that simultaneously supports pedagogy and practicality. The development of a PBL-based interactive e-module is proposed as an

instructional strategy to address these challenges by providing contextual problems, guiding inquiry, facilitating collaboration, and supporting independent learning through multimedia and interactive tasks. The study proceeds through a systematic development process, followed by validity and practicality evaluation by experts and users, and effectiveness testing through classroom implementation focusing on students' biotechnology problem-solving skills. Through this approach, the study aims to strengthen the quality, clarity, and relevance of biotechnology learning while offering a replicable model for integrating PBL with digital learning resources in biology education.

## METHOD

### Research Design and Development Model

This study employed a Research and Development (R&D) approach using the 4D model (Define–Design–Develop–Disseminate) to develop a PBL-based interactive e-module for biotechnology learning. The 4D model was adapted to the study context while preserving the core logic of systematic product development (Sihombing, 2024). Figure 1 presents the overall workflow of the modified 4D process, including expert validation, limited trials, product revision cycles, and field implementation. The development output was a digital interactive e-module that embeds Problem-Based Learning (PBL) phases—problem orientation, problem analysis, investigation, solution design, presentation, and reflection—through structured activities, multimedia elements, and guided questions.



**Figure 1.** 4D design

### Development Procedure

#### *Define Stage*

A needs analysis was conducted to identify learning problems in biotechnology, student learning characteristics, and available school resources (device access, internet stability, and learning time allocation). This stage also included curriculum analysis (learning objectives and competency standards), concept analysis for biotechnology subtopics, and formulation of problem-solving indicators to be targeted by PBL activities. The output of this stage was a specification document consisting of (a) biotechnology learning outcomes, (b) contextual problem themes, (c) problem-solving skill indicators, and (d) constraints for implementation at the research site.

#### *Design Stage*

The e-module structure was designed by mapping (a) biotechnology content sequence, (b) PBL steps, and (c) problem-solving indicators into a coherent learning flow. A storyboard and prototype layout were prepared to define navigation, interactive tasks, multimedia placement

(images/animations/videos), and assessment points. At this stage, the product design also specified technical requirements (file format/platform, offline/online access mode, and device compatibility) to reduce implementation barriers, especially related to video access and internet instability. The output was Prototype-1 of the interactive e-module along with draft instruments for validation, practicality, and problem-solving assessment.

### ***Develop Stage***

Prototype-1 underwent expert review and product revision cycles. Content validity was examined by a subject-matter expert (biotechnology/material expert) and learning design validity by a learning media/design expert. In addition, a biology teacher served as a practitioner reviewer to evaluate classroom feasibility and alignment with school conditions. All qualitative feedback (comments, criticisms, suggestions) was used to revise the module into Prototype-2. After revision, the module was tested in a small-scale trial to examine usability and clarity of instructions, followed by a second revision (Prototype-3) prior to large-scale implementation. The outputs of this stage were the final e-module version for field testing and finalized research instruments.

### ***Disseminate Stage***

The final product was implemented in a classroom setting to evaluate practicality and effectiveness. Dissemination in this study refers to limited dissemination at the research site through classroom use and teacher introduction/training for implementation. Wider dissemination beyond the site was not conducted and is recommended for future studies.

### **Participants and Sampling**

The research was conducted at NW Suralaga High School. Participants consisted of: (a) a small-scale trial group of 15 students to evaluate readability, navigation, and practicality issues; and (b) a large-scale implementation group of 30 students for effectiveness testing. The large-scale group was selected using purposive sampling based on class availability and teacher recommendation to represent typical learners in the school context. Participant characteristics (grade level, age range, and learning setting) were documented during implementation. Because learning media research involves student participation, classroom implementation followed school approval procedures and ensured that student participation and data collection were handled ethically and confidentially.

### **Instruments and Measures**

Three categories of instruments were used: validity instruments, practicality instruments, and effectiveness instruments.

#### ***Validity Instruments (Expert Validation Sheets)***

Validity was assessed using expert judgment forms completed by material experts and media/design experts. The validation sheets covered content accuracy, relevance to curriculum, conceptual clarity, alignment with PBL phases, instructional coherence, language readability, interface design, navigation consistency, and multimedia appropriateness. Each item was rated using a Likert-type scale and accompanied by open-ended comments for revision. Expert feedback was treated as primary evidence for content and design validity and guided iterative product improvement.

#### ***Practicality Instruments (Teacher and Student Response Questionnaires)***

Practicality was measured using questionnaires administered to students and a biology teacher after using the e-module. The practicality questionnaire assessed ease of use, clarity of instructions, time efficiency, attractiveness, accessibility (including internet/video constraints), and perceived usefulness for learning biotechnology through PBL activities. Open-response sections were included to capture implementation barriers and suggestions for improvement.

### ***Effectiveness Instrument (Problem-Solving Skills Test)***

Effectiveness was evaluated using a problem-solving test consisting of 10 descriptive (constructed-response) items designed to measure biotechnology problem-solving performance. The test blueprint was aligned with problem-solving indicators: (a) identifying and defining the problem, (b) gathering and selecting relevant information, (c) proposing and justifying solution strategies, (d) applying biotechnology concepts to the proposed solution, and (e) evaluating outcomes and reflecting on solution limitations. To ensure scoring transparency, responses were evaluated using an analytic rubric that specifies performance criteria and score levels for each indicator. The rubric-based scoring procedure was used consistently for pretest and posttest. Instrument quality was strengthened through expert review of item relevance and clarity, and scoring consistency was maintained by applying the same rubric across all student responses.

### **Data Collection Procedures**

Data collection occurred in three phases: (1) expert validation and revision during the Develop stage; (2) small-scale trial (15 students) to capture usability/practicality issues and refine the product; and (3) large-scale classroom implementation (30 students) to assess practicality and effectiveness. For the effectiveness phase, students completed a pretest before learning with the e-module and a posttest after completing the biotechnology PBL learning sequence. During implementation, the teacher facilitated learning using the e-module, and students engaged in problem scenarios, investigation tasks, collaborative discussion, and reflection activities embedded in the module. Practicality questionnaires were administered after implementation, along with qualitative feedback collection.

### **Data Analysis**

This study applied both qualitative and quantitative analyses. Qualitative data included expert and user comments that informed revisions, while quantitative data summarized validity, practicality, and effectiveness evidence.

### ***Questionnaire Analysis (Validity and Practicality Scores)***

Validator ratings and user questionnaire responses were converted into percentages and interpreted using the eligibility criteria shown in Table 1 (Setiawan et al., 2015). The percentage score was calculated for each aspect and overall feasibility category (Excellent, Good, Enough, Less good, Very bad). Qualitative suggestions from validators and users were used to explain weaknesses and guide targeted revisions.

**Table 1.** Eligibility Criteria (Setiawan et al., 2015)

<b>Percentage of questionnaires</b>	<b>Interpretation</b>
$81\% \leq P < 100\%$	Excellent
$62\% \leq P < 80\%$	Good
$43\% \leq P < 62\%$	Enough
$33\% \leq P < 43\%$	Less good
$P < 33\%$	Very bad

### ***Effectiveness Analysis (Problem-Solving Skills Test)***

Student test scores were analyzed using descriptive and inferential statistics. Descriptive statistics included mean, standard deviation, minimum–maximum scores, and normalized gain (N-gain) to describe improvement magnitude. Inferential analysis tested whether posttest scores differed significantly from pretest scores.

### ***Assumption Testing***

Normality of pretest and posttest score distributions was examined using the Shapiro–Wilk test (recommended for small-to-moderate sample sizes). Homogeneity of variance was evaluated using Levene’s test when required by the selected inferential procedure. Decision

rules applied were:  $p > 0.05$  indicates the assumption is met;  $p \leq 0.05$  indicates the assumption is not met.

### Hypothesis Testing

If normality assumptions were met, the effectiveness of the e-module was tested using a paired-samples t-test (pretest vs posttest within the same group). If assumptions were not met, a non-parametric alternative (Wilcoxon signed-rank test) was applied. Statistical significance was determined at  $\alpha = 0.05$ . To strengthen interpretability beyond p-values, effect size (Cohen's  $d$  for paired designs or  $r$  for Wilcoxon) was calculated and reported to indicate the magnitude of change.

### Interpretation Criteria

Improvement in problem-solving skills was interpreted using (i) statistical significance (p-value), (ii) effect size magnitude, and (iii) normalized gain category (low/moderate/high) to provide a balanced conclusion about learning improvement.

### Methodological Note on Design Limitations

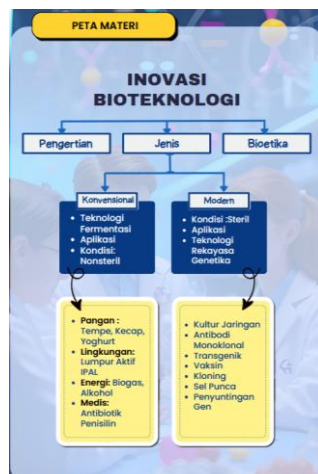
Because effectiveness testing used a one-group pretest–posttest design within limited dissemination, causal claims were bounded. The study therefore interpreted findings as evidence of improvement associated with implementation of the PBL-based interactive e-module, while acknowledging potential internal validity threats (e.g., testing effects, maturation, and history) that should be addressed through future controlled or comparative studies.

## RESULTS AND DISCUSSION

### Product Development Using the 4D Model

#### Define Stage

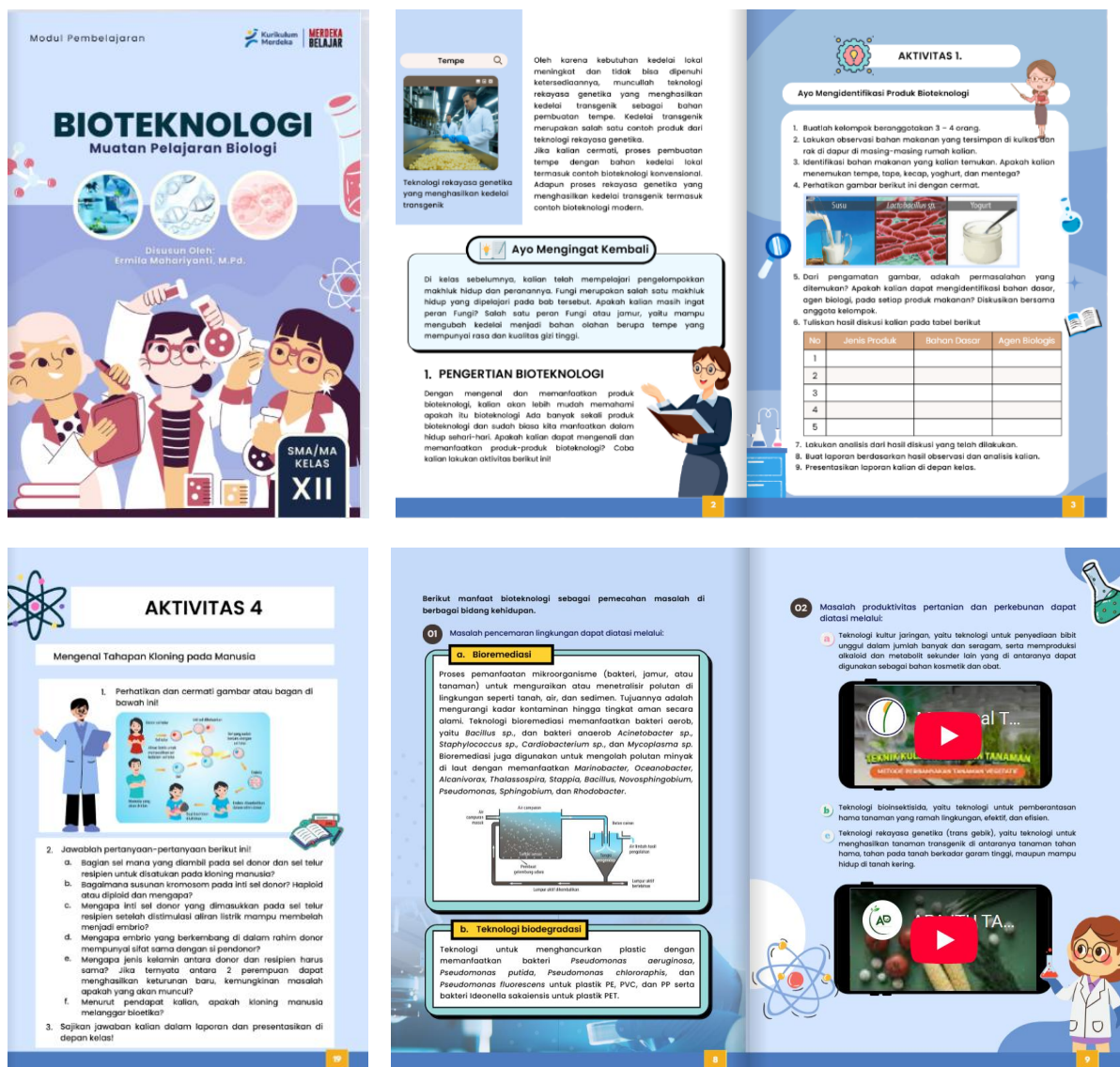
Needs analysis was conducted through teacher interviews and curriculum study. The curriculum analysis focused on learning outcomes for biotechnology and the scope of content required for learning activities designed around contextual problems. A biotechnology content map was produced to organize the selected subtopics and their sequence in the module (Figure 2). Learner analysis was also conducted to identify students' learning characteristics and their readiness to use digital learning resources. The availability of supporting facilities and infrastructure (e.g., access to devices and connectivity conditions) was considered to ensure implementation feasibility. Interview findings indicated that biotechnology learning remained dominated by teacher explanation, students were relatively passive, and available learning media were insufficient to support active learning and the development of problem-solving skills.



**Figure 2.** Biotechnology Material Map

**Design Stage**

The Design stage produced a prototype blueprint of a PBL-based interactive e-module. This stage included: (a) structuring biotechnology content into learning units aligned with the content map; (b) embedding the PBL learning flow through contextual problems, guiding questions, investigation prompts, and reflection activities; and (c) designing interactive elements such as images, animations, and videos to support concept visualization. In parallel, evaluation tools were prepared, including pretest and posttest items, student response questionnaires, and expert/practitioner assessment questionnaires. The prototype design and interface layout are presented in Figure 3, while the organization of module activities based on PBL principles is shown in Figure 4.



**Figure 3. Interactive E-Module Design**

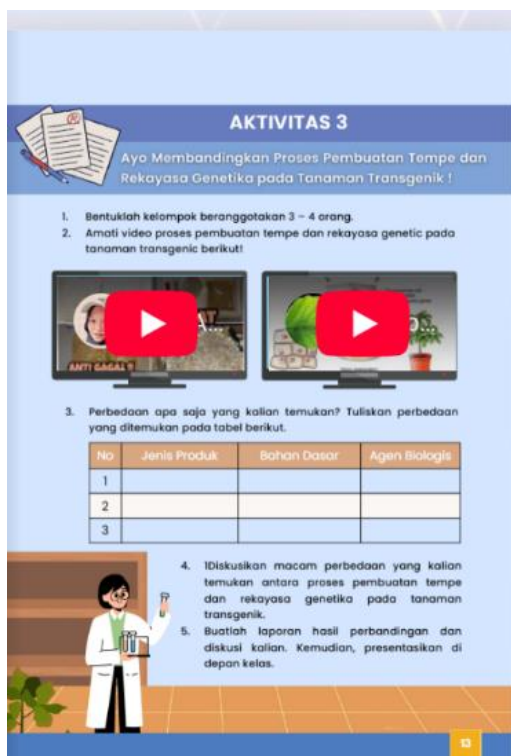


Figure 4. E-Module with PBL principles

**Develop Stage**

The Develop stage consisted of expert validation, revision, and limited (small-scale) trials. The prototype was evaluated by a material expert, a media/design expert, peer reviewers, and a biology teacher. The validation process generated quantitative ratings and qualitative inputs used to revise the module. After revision, a small-scale trial was conducted with students to evaluate readability, attractiveness, navigation clarity, and ease of use. Feedback from the small-scale trial was used for further refinement before wider implementation.

**Feasibility Results**

**Expert Validation Results**

Expert validation covered content feasibility (accuracy, clarity, relevance), presentation/readability, and media/design feasibility (layout, graphics, navigation, and interface). Table 3 summarizes the validation results.

**Table 3.** Percentage results of expert/practitioner assessment of the interactive e-module

Validator	Total Score	Percentage	Criterion
Material Expert	92	76.67%	Good
Media Expert	49	76.56%	Good
Peers	137	76.11%	Good
Biology Teacher	135	75.00%	Good

Overall, the module achieved **Good** feasibility across validators. Qualitative feedback indicated the need to improve writing systematics, align images with explanatory text, and strengthen consistency of structure and presentation.

**Small-Scale Practicality Results (Student Responses)**

Practicality was evaluated through student responses during the small-scale trial (n = 15). The questionnaire measured three aspects: usability (3 items), display/presentation (5 items), and material presentation (13 items). The results are presented in Table 5.

**Table 5.** Student responses to the interactive e-module (small-scale trial, n = 15)

Assessment Aspect	Total Score	Percentage	Criterion
Usability of the e-module	145	80.8%	Good
Display and presentation	243	81.0%	Excellent
Material presentation	619	79.4%	Good

Students generally rated the module as easy to use, visually supportive, and clearly presented. The most frequently reported constraint was that embedded videos played slowly when the internet connection was unstable, so smooth video access required a stable connection.

### Small-Scale Effectiveness Results (Pretest–Posttest)

A small-scale effectiveness test was conducted using 10 descriptive questions administered as a pretest and posttest. Learning implementation using the PBL-based interactive e-module was carried out over three meetings. The comparison of mean scores and gain is shown in Table 4. The results show an increase from a mean pretest score of 56.33 to a mean posttest score of 77.33, with an N-gain of 0.46 (moderate).

**Table 4.** Pretest–posttest comparison in small-scale trial

Statistic	Pretest Mean	Posttest Mean	N-gain
Average	56.33	77.33	0.46

### Large-Scale Implementation Results (Effectiveness Testing)

#### Participants and Implementation

Large-scale implementation was conducted with 30 students selected using purposive sampling. The effectiveness test used a one-group pretest–posttest approach, with pretest administered before learning and posttest administered after learning using the PBL-based interactive e-module.

#### Descriptive Statistics

Descriptive statistics for the large-scale pretest and posttest scores are presented in Table 6. The mean score increased from 50.67 (pretest) to 83.67 (posttest), indicating improved performance after learning with the e-module.

**Table 6.** Descriptive statistics of pretest and posttest scores (n = 30)

Test	N	Minimum	Maximum	Mean	Std. Deviation
Pretest	30	35	70	50.67	9.714
Posttest	30	75	95	83.67	6.008

#### Normality Test

Normality was tested using Shapiro–Wilk (Table 7). Both pretest and posttest distributions were normal ( $p > .05$ ).

**Table 7.** Shapiro–Wilk normality test (n = 30)

Data	Statistic	df	Sig.
Pretest	.955	30	.225
Posttest	.911	30	.061

#### Hypothesis Test Results

Inferential analysis compared learning outcomes using a t-test procedure. Table 9 presents the output used to support hypothesis testing. The significance value obtained was  $p = 0.029$ , which is below the critical limit of 0.05. Therefore, **H<sub>0</sub> was rejected**, indicating a

statistically significant difference in scores after implementation. This result supports that learning using the PBL-based interactive e-module was associated with improved student performance in problem-solving.

**Table 9.** Hypothesis analysis results with t-test

Pair	Variable	Mean	N	Std. Deviation	p
Pair 1	Pretest	50.67	30	9.714	0.029
	Posttest	83.67	30	6.008	

## Discussion

### *Learning Rationale for PBL-Based Interactive E-Modules*

Interactive e-modules are digital teaching materials that go beyond static text by integrating multimedia and interactive components such as videos, animations, quizzes, and simulations. When designed around Problem-Based Learning (PBL), these modules place contextual problems at the center of learning activities and guide students to analyze situations, seek evidence, and construct solutions through both collaborative and independent learning processes (Ramadhan, 2021; Anggraeni et al., 2023). This design is particularly relevant in biology topics that demand conceptual understanding alongside application, because students must interpret information, connect concepts across contexts, and justify decisions using biological reasoning.

In biology learning, problem-solving skills refer to students' capacity to engage with biological situations—ranging from natural phenomena to contextual cases and environmental problems—where solutions are rarely single-step or immediately obvious (Rahayu et al., 2018; Karima, 2020). This competency includes identifying and defining the biological problem, collecting and selecting relevant information, planning solution strategies, applying appropriate methods (including investigative reasoning and, when feasible, experimental or procedural approaches), interpreting findings, and evaluating solution quality through reflection and consideration of alternatives (Rahayu et al., 2018; Trilestari & Almunawaroh, 2020). The logic of a PBL-based interactive e-module is therefore to provide structured experiences that repeatedly engage students in these processes, while using multimedia to reduce abstraction and support comprehension.

### *Feasibility and Practicality in Classroom Use*

The feasibility outcomes (expert judgment) indicate that the module meets acceptable standards in content and media design for classroom implementation. At the same time, aspects such as consistency of presentation, clarity of writing systematics, and alignment between images and explanatory text remain important because an interactive module is intended to support learning navigation and student independence. When the structure of a module is coherent and cues are clear, students can focus their cognitive resources on analyzing problems rather than on figuring out how to use the material.

Practicality findings from students support that the module is generally usable and engaging. This aligns with the expectation that interactive learning media can make students more active and enthusiastic, particularly when learning materials embed videos and contextual problems that encourage students to seek information and propose solutions (Ali, 2019). Interactive e-modules are frequently described as an effective bridge between digital technology and problem-solving-oriented instruction because they can package PBL steps into a guided sequence that students can follow systematically (Astalini et al., 2019; Komikesari et al., 2020; Adawiyah & Anwar, 2021; Trilestari & Almunawaroh, 2020). Moreover, interactive prompts and activities can motivate students to explore information sources, identify key problem elements, and evaluate solution ideas through reflection or discussion (Isnawati et al., 2020).

However, implementation constraints were also evident. Students reported that unstable internet connections slowed video playback, which disrupted access to embedded multimedia. Such constraints are consistent with observations that digital learning effectiveness can be limited by infrastructure variability, particularly when learning media depend on streaming content (Suryani, 2019). This issue has direct instructional implications: if multimedia elements serve as conceptual scaffolds (e.g., illustrating biotechnology processes), then limited access can reduce learning consistency across students. Practical implementation therefore benefits from technical adaptations (e.g., compressed files, offline-access options, or alternative static visuals) to ensure the module remains usable under different connectivity conditions.

### ***Effectiveness and the Mechanism of Problem-Solving Improvement***

The observed improvement from pretest to posttest suggests that learning activities using the PBL-based interactive e-module were associated with better student performance on problem-solving assessments. This pattern is consistent with the theoretical premise that PBL encourages students to engage in reasoning processes that mirror authentic scientific problem solving—identifying issues, gathering evidence, generating solution options, and evaluating outcomes (Rahayu et al., 2018; Karima, 2020). Multimedia and interactive features support this process by clarifying abstract concepts and providing structured prompts that guide inquiry and reflection (Trilestari & Almunawaroh, 2020; Isnawati et al., 2020).

Evidence from related studies also supports the potential of PBL-based interactive e-modules to improve higher-order learning outcomes. Research involving high school students has shown that such modules can significantly strengthen critical thinking, learning outcomes, and problem-solving performance (Rahayu & Yuliati, 2022; Sugihartono & Wahyudi, 2020). The present findings align with this body of evidence, suggesting that embedding PBL scenarios within an interactive module can shift students from passive reception toward active knowledge construction and solution-focused reasoning (Ali, 2019; Ramadhan, 2021; Anggraeni et al., 2023).

### ***Implementation Readiness and Support Needs***

Despite positive learning potential, effective use of PBL-based interactive e-modules depends on teacher readiness and classroom support. Not all teachers are familiar with PBL facilitation or confident in designing and implementing interactive modules, which can limit the pedagogical fidelity of implementation. Therefore, teacher assistance and professional support remain important, particularly for constructing realistic PBL scenarios and guiding students through inquiry, discussion, and reflection phases (Yuliana & Fauziah, 2021). When teachers are supported to implement PBL consistently, interactive modules are more likely to function as intended—not merely as digital textbooks, but as structured environments for developing students' problem-solving competence (Adawiyah & Anwar, 2021; Astalini et al., 2019; Komikesari et al., 2020).

In summary, the findings indicate that PBL-based interactive e-modules have strong potential to support student engagement and problem-solving development in biology learning, while their classroom effectiveness is shaped by both infrastructure stability (Suryani, 2019) and teacher facilitation capacity (Yuliana & Fauziah, 2021).

## **CONCLUSION**

This study developed a PBL-based interactive e-module for biotechnology learning and evaluated its feasibility, practicality, and effectiveness in supporting students' problem-solving performance. Expert appraisal indicated that the product met good feasibility criteria, with percentage scores of 76.56% (media expert), 76.67% (material expert), 76.11% (peers), and 75.00% (biology teacher). In the small-scale trial, students' problem-solving performance improved with a moderate N-gain (0.46). Student response data also showed that the module was practically usable and well received, indicated by 80.8% (usability; good), 81.0% (display

and presentation; excellent), and 79.4% (material presentation; good). In the large-scale implementation, the paired-samples analysis produced a significant result ( $p = 0.029 < 0.05$ ), indicating a meaningful improvement in students' scores after learning with the e-module. Overall, the findings suggest that the PBL-based interactive e-module is feasible for classroom use and is associated with improved student problem-solving performance in biotechnology learning.

## RECOMMENDATION

Future research should strengthen product evaluation by expanding usability and effectiveness testing across more diverse school settings, including variation in internet stability, device availability, and student characteristics. Further studies are also encouraged to employ comparative designs (e.g., control or comparison groups) to provide stronger evidence of effectiveness and to explore which e-module components most strongly influence specific aspects of problem-solving. The application of the developed e-module should be recommended primarily for biology/biotechnology learning contexts and for subjects with similar problem-based characteristics, rather than generalized to all levels and subjects without additional empirical testing.

## ACKNOWLEDGMENTS

I extend my gratitude to all individuals who contributed to this research, including expert validator lecturers, teachers, and students who were involved in the data collection process.

## FUNDING INFORMATION

This research was funded by the Ministry of Higher Education, Science, and Technology via a BIMA grant, and the National Research and Innovation Agency (BRIN) for the 2025 funding year.

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Irwansah		✓		✓		✓	✓	✓	✓	✓		✓		✓

## CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflict of interest related to the research, authorship, or publication of this article

## INFORMED CONSENT

We have obtained informed consent from all individuals included in this study

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