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Development of STEM-integrated project-based learning to improve critical thinking skills of senior high school students on environmental change material

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Abstract

The 21st-century education demands mastery of critical thinking skills to address real-world problems. However, existing learning materials have not yet fully supported the systematic development of these skills. This study aims to develop a Project-Based Learning (PjBL) device integrated with STEM that is valid, practical, and effective in enhancing students' critical thinking skills on the topic of environmental changes. The learning package was comprehensively developed in the form of a module, an interactive e-worksheet, and assessment instruments based on critical thinking indicators. The research employed a Research and Development (R&D) approach using the ADDIE model. The subjects were grade X high school students. Research instruments included validation sheets, practicality questionnaires, and critical thinking tests. The validation results indicated that the developed product was of very high quality, practical to use, and effective in improving critical thinking skills, achieving an n-gain score of 0.70 (high category). All indicators of critical thinking improved significantly, particularly the inference indicator. These findings confirm that the STEM-integrated PjBL into a comprehensive learning package can serve as a strategic innovation to support the implementation of the Kurikulum Merdeka and strengthen 21st-century biology education that emphasizes problem-solving and contextual learning.

Abstrak. *Pendidikan abad ke-21 menuntut penguasaan keterampilan berpikir kritis untuk menghadapi permasalahan nyata. Namun, perangkat pembelajaran yang tersedia belum sepenuhnya mendukung pengembangan keterampilan tersebut secara sistematis. Penelitian ini bertujuan mengembangkan perangkat pembelajaran berbasis proyek (PjBL) terintegrasi STEM yang valid, praktis, dan efektif dalam meningkatkan keterampilan berpikir kritis peserta didik pada materi perubahan lingkungan. Perangkat dikembangkan secara komprehensif dalam bentuk modul, lembar kerja peserta didik elektronik interaktif, dan instrumen asesmen berbasis keterampilan berpikir kritis. Metode penelitian menggunakan pendekatan R&D dengan model ADDIE. Subjek penelitian adalah peserta didik kelas X SMA. Instrumen penelitian meliputi lembar validasi, angket kepraktisan, dan tes keterampilan berpikir kritis. Hasil validasi menunjukkan bahwa produk yang dikembangkan memiliki kualitas sangat baik, praktis digunakan, dan efektif meningkatkan keterampilan berpikir kritis dengan n-gain sebesar 0,70 (kategori tinggi). Seluruh indikator berpikir kritis meningkat secara signifikan, terutama pada indikator inference. Temuan ini menegaskan bahwa PjBL yang terintegrasi STEM dalam satu paket pembelajaran yang utuh dapat menjadi inovasi strategis dalam mendukung implementasi Kurikulum Merdeka dan memperkuat pendidikan biologi abad ke-21 yang berorientasi pada pemecahan masalah dan pembelajaran kontekstual.*

A. Introduction

Contextual learning emphasizes students' active construction of knowledge by connecting subject matter to real-life experiences, making it a student-centered approach aligned with 21st-century education demands that include critical thinking, creativity, collaboration, and communication (Ennis, 2015). However, research indicates that Indonesian students' critical thinking skills remain relatively low, largely due to the dominance of conventional learning tools that fail to stimulate higher-order thinking (Sholikah & Hindriana, 2024; Rahmawati et al., 2021; Velina et al., 2018).

One promising alternative is the integration of STEM (Science, Technology, Engineering, and Mathematics), which equips learners with essential interdisciplinary skills for solving real-world problems and fosters holistic understanding across scientific and technological contexts. Meanwhile, Project-Based Learning (PjBL) engages students in authentic projects to investigate and respond to complex, real-life questions (Tseng et al., 2013). While inquiry-based learning focuses on conceptual exploration through experimentation, PjBL emphasizes the design and implementation of solutions that produce tangible outcomes.

The STEM-integrated PjBL has proven to enhance collaboration, communication, creativity, and critical thinking (Bandjar et al., 2024; Desi et al., 2023; Sholihah et al., 2025). Systematic reviews and meta-analyses (Amelia & Santoso, 2021; Diana et al., 2021; Putri et al., 2021) further affirm the effectiveness of STEM-PjBL in improving conceptual understanding, scientific literacy, problem-solving, and engagement through authentic learning experiences. Specifically, the STEM-integrated PjBL approach is highly relevant to environmental topics, as it enables students to connect scientific concepts to locally relevant environmental issues, fostering ecological awareness and solution-oriented learning (Mutakinati et al., 2018; Herlita et al., 2023; Nehru et al., 2024).

Despite its potential, prior studies have primarily focused on validating learning models or isolated materials rather than developing integrated instructional tools. The novelty of this research lies in its comprehensive integration of a teaching module, an electronic student electronic worksheet, and critical thinking assessment instruments into a single STEM-PjBL package for the topic of environmental change, something not addressed in previous studies by Mutakinati et al. (2018); Herlita et al. (2023); and Sholihah et al. (2025) Unlike those studies, which separately investigated either conceptual understanding, environmental literacy, or student engagement, this research combines multiple dimensions into a cohesive, technology-supported learning system.

This study occupies a strategic position as it integrates pedagogical innovation with digital interactivity to systematically promote the development of students' critical thinking skills. However, the implementation of this learning package requires adequate teacher competence to ensure its effective application across diverse school contexts. The development also aligns with the direction of the Kurikulum Merdeka, which emphasizes inquiry-based, contextual, and project-oriented learning as an effort to strengthen students' independence and creativity. Nevertheless, large-scale implementation may still be hindered by limitations in infrastructure and technological access in certain schools, posing a challenge to the broader adoption of this digitally based learning package.

Based on this background, the study aims to develop a STEM-integrated PjBL package on the topic of environmental change and evaluate its validity, practicality, and effectiveness in improving students' critical thinking skills through N-gain analysis and the Mann–Whitney test.

B. Material and method

A teaching model can be regarded as a structured plan or framework designed to organize the curriculum, develop instructional materials, and guide teachers in facilitating the learning process across various contexts (Joyce, 2009). Based on this perspective, this study employed a STEM-integrated PjBL approach as the foundation for developing the learning tools. The PjBL model was chosen because it emphasizes student-centered learning through authentic projects that require investigation, collaboration, and the application of knowledge to solve real-world problems (Bell, 2010). Its characteristics align with the objectives of this research, namely, to foster students' active participation, critical thinking, creativity, and communication skills.

The STEM-integrated PjBL approach was designed to provide interdisciplinary connections among science, technology, engineering, and mathematics, while simultaneously contextualizing learning within real-life environmental issues (Beers, 2011). Through this integrated model, students were engaged in designing, experimenting, and problem-solving activities relevant to the topic of environmental changes. Consequently, the learning tools developed in this study were expected to meet the criteria of being valid, practical, and effective in enhancing students' higher-order thinking skills, particularly critical and creative thinking.

The development of the learning tools followed the ADDIE model, which includes the stages of Analysis, Design, Development, Implementation, and Evaluation, as proposed by Branch (2009). This model was selected for its systematic and flexible framework that supports iterative refinement while maintaining learner-centeredness and contextual relevance. The final learning package consisted of three integrated components: a printed learning module, an interactive electronic worksheet, and a critical thinking assessment instrument. Each component was designed to align with the competencies outlined in the Merdeka Curriculum for Phase E and to promote scientific inquiry, collaboration, and reflection (see Figure 1).

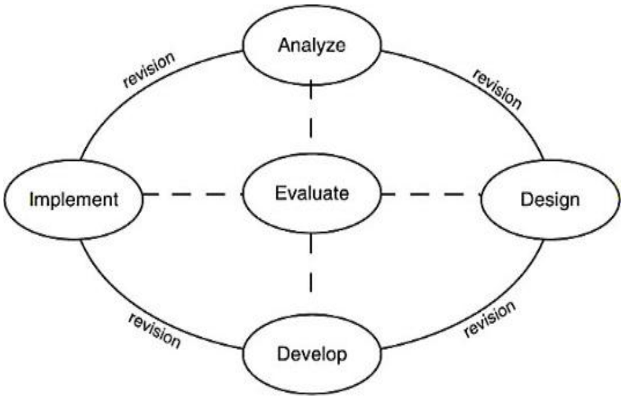

Figure 1
Research and development stage (Adapted from Branch, 2009)

The study was conducted at SMA Angkasa Adisutjipto Yogyakarta from February to March 2025. The population of this study was all students of class X (phase E) of SMA Angkasa in the 2024/2025 academic year, total of 136 students, spread across 4 classes. The sample of this study was 69 students from classes E1 and E2, where class E1 consisted of 34 students and class E2 consisted of 35 students. These Class E1 and E2 were randomly selected/taken from the 4 existing classes. The determination of the experimental and control groups was also carried out randomly, resulting in Class E2 as the experimental group and Class E1 as the control group. The experimental group (E2) was taught using the STEM-integrated PjBL model, while the control group (E1) received learning through the conventional teaching model, namely discovery-based learning. Both groups were taught by the same teacher to minimize instructional bias.

At the implementation stage, a quasi-experimental design with a Non-Equivalent Control Group (Sugiyono, 2019) was applied. In this design, two groups of students were selected without random assignments, with the experimental group receiving the STEM-integrated PjBL intervention and the control group following conventional instruction. This design was chosen because it provides an opportunity to evaluate the effectiveness of the teaching model in real classroom settings, while still allowing comparison of improvements in students' critical thinking skills between the experimental and control groups. Thus, this design is effective for assessing the impact of innovative learning in natural educational contexts, where full randomization is not feasible.

The STEM-integrated PjBL learning procedure was implemented through five structured steps: Reflection, Investigation, Discovery, Application, and Communication. Reflection helps students assess prior knowledge, Investigation promotes data collection and evidence evaluation, Discovery enhances analytical and synthetic skills, Application trains the application of concepts to solve real-world problems, and Communication strengthens reflective and evaluative abilities. Collectively, these steps enhance students' critical thinking, creativity, and collaboration skills in line with 21st-century educational demands

The instruments used in this study included: Validation Sheets, used to assess the validity of the learning tools in terms of content, language, presentation, and graphic design. Validation was carried out by three experts: a subject matter expert, a media expert, and a practitioner, using a four-point Likert scale by Riduwan (2015). Practicality Questionnaire, administered to teachers and students to evaluate the usability, attractiveness, and learning support of the tools. The questionnaire was developed based on aspects of usability, ease of use, and student engagement (Plomp & Nieveen, 2010). The Critical Thinking Skills Test, consisting of essay questions developed based on the indicators of critical thinking, was used as the research instrument. According to Ennis (2015), the Critical Thinking Skills Test consisted of 5 essay items designed to assess students' ability to analyze, reason, and evaluate problems related to environmental change. Student responses were scored using analytic rubric covering five dimensions: elementary clarification, basic support, inference, advanced clarification, and strategy and tactics. Each dimension was rated on a 0–4 scale. The final scores were classified into three categories: High (75–100), Medium (50–74), and Low (<50).

The development stages followed the ADDIE model: Analysis Stage: Needs analysis was conducted through classroom observation, curriculum review, and questionnaires administered to teachers and students to identify problems in biology learning, especially on environmental change topics. Design Stage: Learning tools were designed in the form of a teaching module and electronic worksheet using the Liveworksheet platform, complemented with critical thinking assessment instruments. The design followed principles of STEM-integrated PjBL. Development Stage: Tools were developed using Canva and Liveworksheet applications. This stage involved expert validation, tool revision, and an initial readability test by teachers and students. Implementation Stage: The tools were tested in the experiment group to collect data on practicality and effectiveness. Teachers implemented the learning using the developed tools, while the control group used conventional materials. Evaluation Stage: Evaluation was conducted through analysis of validity, practicality, and effectiveness data. Final revisions were made based on feedback from validators, teachers, and students to refine the learning tools.

Data Analysis Techniques The validity of the tools was analyzed descriptively and quantitatively by calculating the average score from validation sheets using a 4-point Likert scale (Riduwan, 2015). A tool was considered very valid if the average score was ≥ 3.26.

Practicality was analyzed from teacher and student questionnaire responses. The practicality test involved one science teacher and 69 Grade X students who participated in the trial. The questionnaire assessed the ease of use, clarity of instructions, suitability of content, and attractiveness of the developed learning tools. and categorized as very practical if the average score reached ≥ 81% of the maximum score (Plomp & Nieveen, 2010).

Effectiveness was analyzed using two complementary approaches. The N-Gain test was applied to measure the improvement in students' critical thinking skills from pre-test to post-test, while the Mann–Whitney U test was used to determine the significance of differences between the experimental and control groups. The selection of the Mann–Whitney U test was based on the results of the Kolmogorov–Smirnov and Levene tests, which showed that the data did not meet normality and homogeneity assumptions (Sugiyono, 2019). Therefore, a non-parametric approach was considered more appropriate than parametric alternatives such as ANCOVA, as it avoids assumptions of normal distribution and equal variances that could compromise result validity. The gain score was calculated using Formula 1, the normalized gain formula (Hake, 1998; Miller et al., 2016).

$$< g > = \frac{\text{Sf} - \text{Si}}{\text{Smax} - \text{Si}} \dots\dots\dots\dots\dots\dots \text{Formula 1}$$

Description
$< g >$ = normalized gain score
Sr = post-test score
Si = pre-test score
Smax = maximum score

Table 1 Gain index criteria

Gain score interval	Category
g > 0.70	High
0.30< g ≤ 0.70	Medium
g ≤ 0.30	Low

C. Results and discussion

The research results are presented according to the stages of reserach & development research, they are: *Analyze, Design, Development, Implement, and Evaluate*. Evaluation results are reported for each stage to ensure a comprehensive understanding of the development and validation process.

Analyze results

The analysis phase identified students' characteristics, initial learning needs, and curriculum alignment. The curriculum analysis revealed that the topic of Environmental Changes aligns with the learning outcomes for Phase E of the Merdeka Curriculum. The student analysis showed that most learners were passive during lessons, exhibited relatively low critical thinking skills, and required innovative, PjBL models to promote engagement. These findings are consistent with Sa'adah et al. (2020) and Windiani & Suniasih (2022), who emphasized that teacher-centered instruction limits the development of 21st-century skills. Similarly, Syofyan et al. (2020) highlighted the importance of student-centered approaches in environmental education to enhance students' engagement with real-world problem-solving. School condition analysis confirmed that ICT facilities were adequate and teachers were accustomed to implementing digital learning tools. Based on these findings, the development of STEM-integrated PjBL tools was deemed necessary to foster active learning and higher-order thinking skills. Table 2.

Tabel 2 Results of the analysis stage

Aspect analyzed	Findings
Curriculum analysis	The environmental changes topic aligns with the learning outcomes of phase e.
Student needs analysis	Students tend to be passive, have low critical thinking skills, and require learning innovations.
School condition analysis	ICT facilities are adequate, and teachers are accustomed to using electronic modules/e-worksheets.

In accordance with the characteristics and student's initial needs and the support of school facilities (Table 2), learning innovation in the form of developing STEM-integrated PjBL approach needs to be implemented.

Design results

The learning tools were designed based on the STEM-integrated PjBL syntax, which includes reflection, research, discovery, application, and communication, supported by digital tools such as Canva and Liveworksheet. These components were structured to promote inquiry, problem-solving, and collaboration, aligning with the framework proposed by Apmiyanti & Yerimadesi (2024). The learning module components consisted of an introduction, learning materials (Part 1 and Part 2), practice questions, self-assessment, evaluation, glossary, and references. Meanwhile, the electronic worksheet components included user instructions, the STEM-integrated PjBL syntax, glossary, learning objectives, and STEM-integrated PjBL activities (see Figure 2 and Figure 3).

Figure 2
Cover and introduction of learning module (in Indonesian)

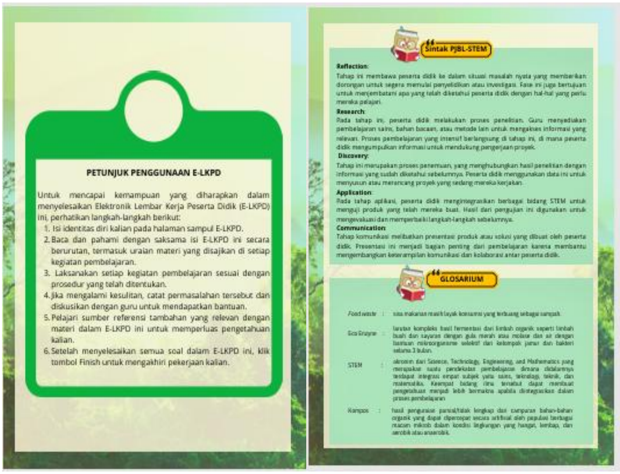

Figure 3
User instructions and STEM-integrated PjBL syntax
(in Indonesian)

The main section of the STEM-integrated PjBL electronic worksheet contains learning activities related to environmental change material, particularly subtopics of environmental issues. These activities span seven pages and correspond to each stage of the STEM-integrated PjBL syntax. The following explains each stage in detail: Reflection: This stage presents an article highlighting an environmental issue, prompting students to propose solutions. Students answer critical thinking questions (elementary clarification). Research: This stage introduces food waste processing methods, including brief explanations and two clickable instructional videos. Students complete a research task, practicing critical thinking (basic support). Discovery: Students design a food waste processing project incorporating STEM aspects. They are required to outline the science, technology, engineering, and mathematics elements of the project. This stage fosters critical thinking (inference). Application: Students create a report of their chosen food waste processing method in the form of a video, infographic, or Canva presentation. Additional critical thinking questions (advanced clarification) are included. Communication: In this stage, students present their project outcomes using a video, infographic, or Canva presentation, encouraging critical thinking (strategy and tactics).

At the design stage, instruments were also prepared for validating learning devices, including practicality tests and limited tests. The validity category refers to (Riduwan, 2015), as Table 3.

Tabel 3 The validy category

Score	Category
85 – 100	Very valid
70 – <85	Valid
50 – <70	Quite valid
30 – <50	Less valid
<30	Not valid

The practicality category of learning tools, refers to Nieveen (1999) and Nieveen & Plomp (2013), as Table 4.

Tabel 4 The practicality category of learning tools

Score	Category
81–100	Very practical/Very good
61–80	Practical/good
41–60	Quite practical/Quite good
≤40	Not practical/Not good

Develop results

The *Develop* stage focused on presenting results of elaboration and expert validation of the designed learning tools. This stage also includes the presentation of the results of practicality tests and limited trials of learning devices. The validation was carried out by subject matter experts, language experts, and media experts. The practicality and limited tests involved teachers (as practitioner) and students (as user).

Results of the validation of learning tools in the form of teaching modules (lesson plans) and electronic worksheet, for the STEM-integrated PjBL, by material experts and media experts are presented in Table 5 and Table 6.

Table 5 Results of validity assessment on the material aspect

No.	Aspect	Score	Category
1–5	Accuracy of the material	90	Very valid
6–14	Presentation of the material	85	Very valid
15	Relevance of facts to concepts on environmental change material	75	Valid
16–18	Language	90	Very valid
	Average	**85**	**Very valid**

The results of the feasibility assessment on the material aspect (Table 5) show that the developed learning tools achieved an average score of 85 with the criterion of very valid. the results of the feasibility assessment on the media aspect (Table 6) indicate that the developed learning tools achieved an average score of 100 with the category of very valid.

Table 6 Results of validity assessment on the media aspect

No.	Assessment aspect	Score	Criteria
1	Display quality	100	Very valid
2	Language	100	Very valid
3	Ease of operation	100	Very valid
4	Application reliability	100	Very valid
5	Illustration quality	100	Very valid
6	Ease of use	100	Very valid
	Average	**100**	**Very valid**

The validation results indicate that the learning tools are highly feasible. Improvements were made based on feedback, such as simplifying language, adding a glossary and visual illustrations, and enhancing lay-out and interactivity. Positive student responses toward the electronic worksheet align with Tunnisa et al. (2022), who found that technology use enhances motivation and conceptual understanding through visual and contextual representation.

Overall, the validation results on both aspects confirm that the STEM-integrated PjBL module and E-Worksheet developed in this study meet the criteria of very valid quality in terms of material and media. The results of the validity test of the learning device show that the learning device is declared very valid. Thus, the trial can be continued to the next development stage, namely the practicality test. Results of the practicality test of learning tools in the form of teaching modules and electronic worksheet, for the STEM-integrated PjBL, by biology teachers are presented in Table 7 and Table 8.

Table 7 Practicality assessment results by biology teacher

No.	Aspect	Score	Criteria
1–4	Material/content	93.8	Very practical
5–7	Language	87.5	Very practical
8–13	Media	87.5	Very practical
14–20	Learning	91.0	Very practical
	Average	**89.95**	**Very practical**

Table 7 shows that the average score is 89.95 (it means very practical). The learning content was evaluated as clear, systematic, and aligned with learning outcomes, covering all objectives with contextual examples. The module and E-Worksheet were also considered engaging because they integrated articles, images, and videos, making them more attractive and easier for students to use compared to traditional text-heavy formats. From the media perspective, the tools were found to be user-friendly, employing communicative language and a design that facilitated understanding. Importantly, in terms of pedagogy, the tools supported student-centered learning through STEM-integrated PjBL, which encouraged active student participation and promoted meaningful learning experiences. The results of the teacher's assessment demonstrate that the STEM-integrated PjBL tools are of high quality and meet the requirements for classroom implementation.

The assessment of the STEM-integrated PjBL tools by students was carried out using a questionnaire consisting of statements categorized into six aspects: attractiveness of material and scientific issues, language, ease of operation/use, attractiveness of the learning tools, flexibility, and interaction. The results of the student assessment are presented in Table 8.

Table 8 Feasibility assessment results by senior high school students

No.	Assessment aspect	Score	Category
1–4	Attractiveness of material and scientific issues	87	Very good
5	Language	86	Very good
6–8	Ease of operation/use	81.5	Very good
9–13	Attractiveness of learning tools	81.5	Very good
14	Flexibility (accessible anytime and anywhere)	77.8	Good
15	Interaction	75	Good
	Average	**81.5**	**Very good**

The student assessment results showed that the STEM-integrated PjBL tools obtained an average score of 81.5 (very good). All aspect including attractiveness of material and scientific issues, language, ease of use, and overall design were rated as very good, while flexibility and interaction were rated as good.

The results indicate that the tools are feasible to be used with only minor revisions. Expert validation is an essential stage in the development of learning materials, as it ensures content accuracy, clarity of language, and media appropriateness before classroom implementation (Sugiyono, 2019; Nieveen & Plomp, 2013). This finding is consistent with previous studies, that high validity scores from experts reflect the quality of STEM-integrated learning tools in supporting students' higher-order thinking skills (Nieveen, 1999; Reeves, 2006).

A limited trial was conducted in the experiment group, to complete the validation of the learning, using a quasi-experimental non-equivalent control group design. The learning implementation achieved 100% compliance with the module, and the teacher confirmed that the tools were easy to implement. Students responded positively to the electronic worksheet, indicating that it enhanced engagement, motivation, and conceptual understanding, consistent with previous studies on technology-based learning tools (Plomp & Nieveen, 2010; Rahmawati et al., 2021). Students showed active participation in exploration and problem-solving, demonstrating the practicality of the product. This results indicate that the tools are feasible to be used in class, to test its effectiveness to students' critical thinking sklls, through an experiment. The results of measuring students' critical thinking skills in the experimental group (using the STEM-integrated PjBL model) and the control group (using the conventional teaching model), before and after class (pre-test and posttest), are presented in Table 9.

Table 9 Students' critical thinking skills in experiment and control group, before and after class

Statistic	Score of critical thinking skills			
	Control group		Experiment group	
	Pre-test	Post-test	Pre-test	Post-test
Minimum	30	75	20	75
Maximum	75	90	85	100
Average	55	78.68	62.86	88.57
Std. Dev.	11.87	4.14	15.26	7.43

Table 9 shows that the average posttest score of students' critical thinking skills from the experiment group (88.57) was higher than that of students in the control group (78.68). In other words, there is a tendency that students who learn with STEM-integrated PjBL model perform better than students who use conventional teaching models. However, the effectiveness of the STEM-integrated PjBL model to critical thinking skills needs to be tested using inferential statistical tests.

The inferential statistical test to test the effectiveness of the STEM-integrated PjBL model on students' critical thinking skills was designed using the *Independent Samples T-test*, when the test prerequisites were met. However, from the calculation it was known that the test prerequisites, both the normality of data distribution and the homogeneity of variance, were not met, therefore the non-parametric test, *Mann Whitney Test* was used. The results of the Mann Whitney Test are shown in Table 10.

Table 10 Results of the Mann-Whitney test results on critical thinking skills

	Critical thinking skills
Mann-Withney U	181.500
Z	-5.095
Asymp.Sig(2-tailed)	.001

Table 10 shows that The Mann-Whitney test yielded a significant difference, with a significance value of 0.001 or $p<0.05$. These test results indicate that the average of the students' critical thinking skills score of the experimental group was significantly higher than that of the control group.

The results of the N-Gain score calculation also show an increase in the average critical thinking skills score of students in the experimental group, which is better compared to the average score of students in the control group. The results of the N-Gain score calculation are presented in the following Table 11.

Table 11 Pre-test, post-test, and N-Gain of students' critical thinking skills

Group	Pre-test	Post-test	N-Gain	Category
Experiment	62.86	88.57	0.70	High
Control	55.00	78.68	0.51	Medium

Table 11 shows that the experiment group achieved an N-Gain score of 0.70 (high category), while the control group obtained only 0.51 (medium category). The results of this study indicate that the improvement of critical thinking skills in the experiment group was higher compared to the control group. This is evidenced by the N-Gain score of 0.70 in the experiment group, which falls into the high category, while the control group only reached 0.51, classified as medium. These findings confirm that the STEM-integrated PjBL model has a significant impact on the development of students' critical thinking skills.

The significant improvement observed in the experiment group demonstrates that students were better facilitated in conducting analysis, evaluation, and logical reasoning. According to Ennis (2011), critical thinking is an active cognitive process of identifying, connecting, and evaluating information to make rational decisions. The PjBL allows students to be directly involved in solving real-world problems, thereby fostering the optimal development of critical thinking processes.

This finding is consistent with the study of Tseng et al. (2013), which emphasized that the STEM-integrated PjBL approach enhances critical thinking skills through the integration of theoretical concepts with everyday contexts. Furthermore, a recent meta-analysis demonstrated that PjBL has a positive and significant effect on critical thinking skills, with a moderate effect size (SMD ≈ 0.387, $p < 0.001$) (Lou et al., 2024). This is also reinforced by a local study conducted by Apmiyanti & Yerimadesi (2024), which reported that innovative PjBL tools could effectively facilitate students in improving their critical and creative thinking abilities.

Meanwhile, the relatively lower improvement of critical thinking skills in the control group indicates that conventional teaching methods still tend to emphasize lower-order cognitive aspects. This condition is in line with Arends & Kilcher (2010), who noted that traditional instruction is more oriented toward the transfer of knowledge, thereby providing limited opportunities for the development of higher-order thinking skills.

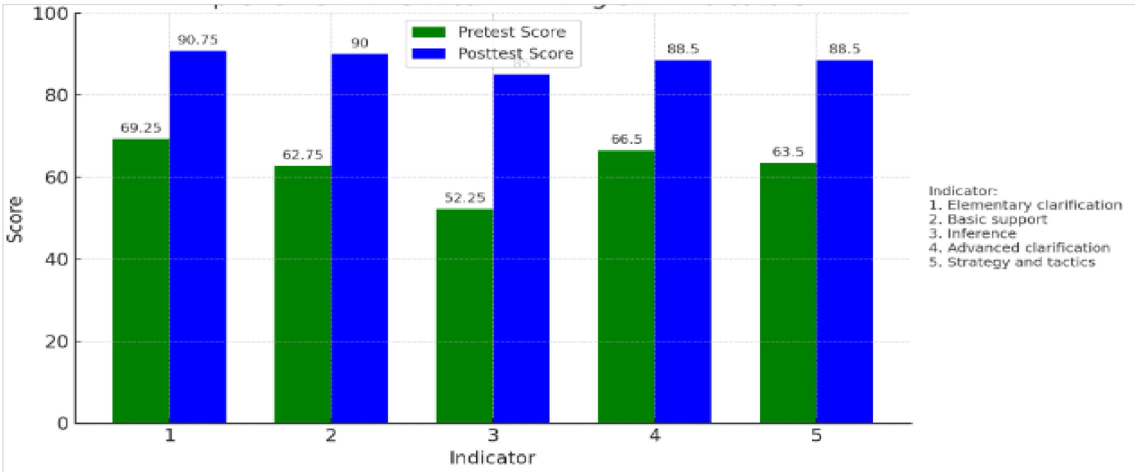

Figure 4
Increase in students' critical thinking skill indicators before and after using the STEM-integrated PjBL tools

From the analysis of critical thinking skill indicators of students in the experiment group showed the greatest improvement in inference (62.67%), suggesting a substantial enhancement in students' ability to draw conclusions from data or information. This aligns with Sholihah et al. (2025) who reported that STEM-integrated PjBL tools effectively improve students' reasoning and problem-solving abilities.

Overall, the developed learning tools were proven to be valid, practical, and effective in enhancing students' critical thinking skills. This study hypothesizes that the implementation of STEM-integrated PjBL significantly improves students' higher-order thinking skills in science learning (see Figure 4). This finding is consistent with previous studies by Lestari et al. (2024) and Kurniahtunnisa et al. (2023), which demonstrated that STEM-integrated PjBL effectively enhances critical thinking, problem-solving, and analytical abilities. Through STEM-integrated PjBL, students are provided with opportunities to explore, analyze, and communicate their learning outcomes critically and creatively. The implementation of this model also contributed to improving students' communication skills, as they actively discussed, presented, and shared their project outcomes—practices that reinforce collaboration and clarity in conveying ideas, aligning with the 21st-century competencies emphasized in the Merdeka Curriculum (Kemendikbudristek, 2022)

The key features of the developed module that contributed to the improvement of students' critical thinking skills include the contextual project design, integration of STEM concepts, and structured scaffolding of activities. The contextual projects allowed students to connect scientific concepts with real-life environmental issues, which stimulated curiosity and encouraged the identification of relevant problems. The integration of STEM disciplines guided students to analyze issues from multiple perspectives, design innovative solutions, and test them systematically. In addition, scaffolding components such as guiding questions, step-by-step investigations, and reflective tasks supported students in developing reasoning, evaluating evidence, and drawing logical conclusions.

In relation to Ennis (2011) critical thinking framework, the developed STEM-integrated PjBL tools addressed five key indicators of critical thinking: elementary clarification, basic support, inference, advanced clarification, and strategy and tactics. The reflection phase facilitated elementary clarification by encouraging students to identify problems, define key concepts, and formulate guiding questions related to environmental issues. During the research phase, students gathered information and evidence to provide basic support for their ideas, strengthening their ability to justify claims with relevant data. The discovery stage promoted inference skills as students analyzed patterns, interpreted findings, and drew logical conclusions from their investigations. The application stage supported advanced clarification by enabling students to connect scientific concepts to real-world contexts and evaluate the validity of their reasoning. Finally, the communication phase fostered strategy and tactics, where students reflected on their learning process, formulated arguments, presented their findings effectively, and engaged in constructive feedback with peers. This systematic alignment demonstrates that the STEM-integrated PjBL model effectively nurtures all dimensions of critical thinking as conceptualized by Ennis, promoting both analytical depth and metacognitive awareness.

Furthermore, the implementation of the PjBL STEM package aligns closely with the principles of the Merdeka Curriculum, which emphasizes student-centered, project-based, and differentiated learning. By involving students in authentic, collaborative, and interdisciplinary tasks, this model supports the development of the Profil Pelajar Pancasila competencies, particularly critical thinking, creativity, collaboration, and communication. The integration of local environmental contexts strengthens students' contextual understanding and sense of relevance, confirming that the PjBL STEM model serves as an effective pedagogical approach for achieving meaningful and transformative learning outcomes aligned with Indonesia's educational goals.

D. Conclusion

The STEM-integrated PjBL tools developed in this study effectively addressed the research problem of enhancing students' critical thinking skills in biology learning on environmental change. The integrated package, which combined a printed module, an interactive electronic worksheet, and a critical thinking assessment, proved valid, practical, and effective, highlighting its novelty as a comprehensive learning innovation. This approach not only strengthened higher order thinking and problem solving but also supported the goals of the Merdeka Curriculum in fostering future ready learners. The developed model offers a scalable framework for promoting contextual and interdisciplinary learning in biology education.

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