JoSSEd
Journal of Science and Science Education
ISSN: 2774-1869 eISSN: 2774-2105

Development of Science Teaching Materials Using a Project-Based Learning Model Integrated with STEM to Improve Students' Scientific Literacy and Critical Thinking Skills

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Received: April 15, 2025
Revised: September 27, 2026
Accepted: October 9, 2026
Published: October 31, 2026

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DOI: 10.29303/jossed.v7i2.14998

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Abstract: The low level of scientific literacy and critical thinking skills of students demands the development of contextual teaching materials that are in accordance with the demands of 21st-century learning. This study aims to develop science teaching materials with a Project Based Learning model integrated with STEM that is feasible, practical, and effective to improve students' scientific literacy and critical thinking skills. This study is development research using the 4D model (Define, Design, Develop, Disseminate). The trial subjects consisted of 42 eighth-grade junior high school students selected through convenience sampling techniques. The feasibility test was carried out through expert validation, practicality through observation of learning implementation and teacher and student response questionnaires, while effectiveness was analyzed using N-gain. The results showed that the developed teaching materials had a very high level of validity with a value of 0.914 and a percentage of agreement of 94.30%. The practicality of the teaching materials was also classified as very high, indicated by the learning implementation of 93.75%, teacher responses above 96%, and student responses above 90%. In addition, the teaching materials were proven to be effective in improving scientific literacy (N-gain 0.79) and critical thinking skills (N-gain 0.76) in the high category. Thus, science teaching materials with the STEM-integrated PjBL model are feasible, practical, and effective in improving students' scientific literacy and critical thinking skills, and can be used as an innovative alternative in science learning.

Keywords: Critical thinking skills; PjBL-STEM; Scientific literacy; Science teaching materials

Introduction

Twenty-first-century education demands that young people possess scientific literacy and critical thinking skills to face increasingly complex global challenges (Purwanto et al., 2023; Valladares, 2021; González-Pérez & Ramírez-Montoya, 2022; Hu & Bi, 2025; Sjögren et al., 2023). Scientific literacy encompasses the ability to understand basic scientific concepts, apply them in everyday life, and make informed decisions (Ke et al., 2021; OECD, 2023; Robert & Bybee, 2014). Critical thinking skills involve the ability to analyze, evaluate, and synthesize information to effectively solve problems (Facione, 2011; Halpern, 1998; Halpern, 2013; Lai, 2011; Sharma et al., 2022). However, the reality is that Indonesian students' scientific literacy and critical thinking skills remain at alarming levels (Ramli & Susanti, 2022; Astutik et al., 2025).

Survey results from the Organisation for Economic Co-operation and Development (OECD) through the Programme for International Student Assessment (PISA) reveal that Indonesian students' scientific literacy scores in 2015 and 2018 were 402 and 396, respectively. This trend continued in PISA 2022, where the score dropped to 383, still below the international average. This decline highlights the need for further efforts to improve the quality of education in Indonesia (Hardinata et al., 2023; Solihin et al., 2024; OECD, 2023).

How to Cite:
Sabrina, A., Susilawati, S., & Bachtiar, I. Development of Science Teaching Materials Using a Project-Based Learning Model Integrated with STEM to Improve Students' Scientific Literacy and Critical Thinking Skills. *Journal of Science and Science Education*, *7*(2), 87–96. https://doi.org/10.29303/jossed.v7i2.14998

Critical thinking skills show a similar pattern. Several studies indicate that the level of achievement of critical thinking skills in learning remains low. Ariani (2020) reported that high school students' critical thinking skills were in the low category, with an achievement percentage of 31.38%. In addition, Basri & As'ari (2019) found that junior high school students' critical thinking skills were also low, particularly in evaluation, analysis, and self-regulation sub-skills. This indicates that although various efforts have been made, they have not yet resulted in significant improvements in students' critical thinking abilities.

This condition is also reflected in classroom practices, including at the junior high school level. Observations show that students' learning outcomes have not improved significantly, particularly in terms of scientific literacy and critical thinking skills. Although various strategies have been implemented, such as the use of digital learning media, experiments, group discussions, and independent assignments, the results have not been optimal. This is due to several main factors. First, the strategies used are still fragmented and not integrated into a holistic approach such as Project-Based Learning (PjBL) and STEM, so students do not gain comprehensive and applicable learning experiences. Second, the teaching materials used still focus on theoretical understanding without providing sufficient opportunities for exploration, collaboration, and real-world application. Third, the assessments used have not fully emphasized the measurement of critical thinking skills and scientific literacy in depth, thus limiting their effectiveness.

The development of science teaching materials based on a STEM-integrated PjBL model is one solution to address these issues. PjBL provides opportunities for students to learn through real experiences, solve problems, and develop projects relevant to their lives (Guo et al., 2020; Purwaningsih et al., 2020; Hussein et al., 2024; Asfihana et al., 2022). The integration of STEM makes learning more meaningful by connecting science with technology, engineering, and mathematics. This approach allows students to understand theories while applying them in practical contexts (Davidi et al., 2021; Kelley & Knowles, 2016; McDonald, 2016; Becker & Park, 2011; Le et al., 2023).

Science teaching materials based on the STEM-integrated PjBL model are designed to meet the demands of 21st-century learning, emphasizing both conceptual mastery and practical skills. This approach provides active and collaborative learning experiences, where students can identify real-world problems, design solutions, and evaluate outcomes through meaningful projects. In this context, teaching materials serve as the main guide for both students and teachers in implementing project-based learning integrated with STEM (Priatna et al., 2020; Lou et al., 2017; Wieselmann et al., 2022). Innovative and relevant teaching materials can enhance student engagement, strengthen learning motivation, and deepen understanding of scientific concepts (Meichtry, 1993; Fitria et al., 2023). In line with previous studies, the implementation of PjBL-STEM has been proven to have a positive impact on student learning outcomes.

Several studies support the effectiveness of this approach. Kurniahtunnisa et al. (2023) found that PjBL-STEM learning effectively develops high school students' creative, collaborative, and communicative skills at a high level. Furthermore, studies by Al-Ali (2024) and Hebebci & Usta (2022) show that the integration of STEM in project-based learning helps students develop analytical skills, creativity, and problem-solving abilities. These findings strengthen the assumption that teaching materials based on a STEM-integrated PjBL model have great potential to improve Indonesian students' scientific literacy and critical thinking skills.

However, the implementation of PjBL-STEM teaching materials still faces several challenges. Limited technological infrastructure in educational settings is a major obstacle to implementing project-based learning (Riduan & Othman, 2024; Astuti et al., 2023). In addition, the limited availability of teaching materials specifically designed to support this approach is another challenge that needs to be addressed (Ali et al., 2024; Ansya & Salsabilla, 2024). Therefore, developing teaching materials that are relevant to students' needs and characteristics is a strategic step to ensure the successful implementation of the STEM-integrated PjBL model in science learning.

Overall, the development of science teaching materials based on a STEM-integrated PjBL model is expected to make a significant contribution to improving the quality of science education in Indonesia. With an innovative and applicable approach, these teaching materials are not only capable of enhancing students' scientific literacy and critical thinking skills but also of preparing them to face the challenges of the 21st century.

Method

This study is a research and development (R&D) study aimed at producing science teaching materials based on a STEM-integrated Project-Based Learning (PjBL) model that are valid, practical, and effective in improving students' scientific literacy and critical thinking skills. The trial subjects consisted of 42 students of class VIII-A at SMP 6 Mataram, selected through a convenience sampling technique. The development method referred to the 4D model (Define,

Design, Develop, Disseminate) proposed by Thiagarajan, Semmel, and Semmel (1974).

Research Procedure

In the define stage, the focus was on identifying learning needs as the basis for product development. The initial analysis was conducted through interviews with eighth-grade science teachers to obtain an overview of the learning conditions, students' levels of scientific literacy and critical thinking skills, and the need for innovative teaching materials aligned with 21st-century learning demands. Furthermore, a learner analysis was conducted on 42 students aged 13–14 years using a questionnaire with a 1–4 scale. Task analysis involved examining basic competencies, learning indicators, and STEM-based project activities relevant to the topics of work, energy, and simple machines. Concept analysis was carried out by reviewing curriculum documents and textbooks to map the concepts of work, energy, and simple machines integrated into the STEM-based PjBL teaching materials. Based on these analyses, learning objectives were formulated in accordance with learning outcomes, scientific literacy competencies, and critical thinking skills.

The design stage aimed to produce the initial draft of the product. At this stage, criterion-referenced tests were developed, consisting of 20 multiple-choice questions to measure scientific literacy and 6 essay questions to assess critical thinking skills. Instrument development involved preparing test blueprints, writing test items, and conducting expert reviews to ensure alignment with the defined indicators. In addition, the selection of learning media included printed modules, STEM-based project worksheets, infographics, and experimental simulations to support contextual and applicable learning. The teaching material format was systematically structured to include concept maps, learning objectives, core materials, PjBL-STEM steps, virtual experiment activities on forms and transformations of energy using PhET simulations, STEM projects such as designing a solar-powered power bank and a mini lift, reflection, and evaluation.

The develop stage aimed to produce a product that meets the criteria of validity, practicality, and effectiveness. Feasibility testing was conducted through validation by three physics experts who assessed content appropriateness, alignment with the PjBL-STEM model, presentation, and language. Practicality testing was conducted through teacher and student response questionnaires as well as observation sheets on the implementation of learning. Effectiveness testing was carried out using N-gain analysis to determine improvements in students' scientific literacy and critical thinking skills based on pretest and posttest scores.

The disseminate stage was conducted by implementing the product in another school to test the consistency of its practicality and feasibility in a different context. The implementation involved 40 students of class VIII-F at SMPN 2 Mataram and two science teachers.

Data Analysis Techniques

This study employed analyses of needs, feasibility, practicality, and effectiveness. The need for development was obtained from teacher interviews (analyzed descriptively) and student questionnaires (analyzed using percentages). The percentage formula used is as follows:

$$Response\ score = \left(\frac{total\ score\ obtained}{maximum\ possible\ score}\right) \times 100\% \quad (1)$$

Based on these calculations, the level of development needs was then classified according to predetermined criteria. The categories of development needs are presented in Table 1.

Table 1. Categories of Development Needs

Percentage Result	Category
76-100%	Very high
51-75%	High
26-50%	Low
0-25%	Very low

(Source: Adapted from Arikunto, 2010)

Product feasibility was assessed by experts through validity and reliability testing. Validity was calculated using Formula 2.

$$Validation = \frac{score\ obtained}{maximum\ score} \quad (2)$$

The criteria for feasibility assessment based on percentages are presented in Table 2. A product is considered feasible if it meets the validity criteria.

Table 2. Validation Criteria

Score Range	Validity Level
0.81-1.00	Very valid
0.61-0.80	Valid
0.41-0.60	Fairly valid
0.21-0.40	Less valid
0.00-0.20	Invalid

(Source: Adapted from Gulo & Harefa, 2022)

Reliability was calculated using the Percentage Agreement (PA) formula based on Borich (1994), as follows (Formula 3).

$$Percentage\ Agreement\ (PA) = \left(1 - \frac{A-B}{A+B}\right) 100\% \quad (3)$$

where A represents the highest score and B represents the lowest score. An instrument is considered reliable if the PA value is ≥ 75% (Setiawan et al., 2020).

Furthermore, practicality data were obtained from teacher and student response questionnaires as well as observations of learning implementation, using the following formula:

$$Average\ percentage = (\frac{total\ score\ obtained}{maximum\ score}) \times 100\% \quad (4)$$

The categories of practicality for the STEM-integrated PjBL teaching materials based on response scores are presented in Table 3.

Table 3. Practicality Assessment Categories

Percentage Result	Practicality Category
81% - 100%	Very practical
61% - 80%	Practical
41% - 60%	Fairly practical
21% - 40%	Less practical
<20%	Not practical

(Source: Adapted from Akbar, 2013).

Effectiveness was analyzed using the N-gain test. The N-gain formula, referring to Sundayana (2014), is as follows:

$$N - gain\ (g) = \frac{posttest\ score - pretest\ score}{maximum\ score - pretest\ score} \times 100\% \quad (5)$$

The N-gain criteria and the interpretation of effectiveness are presented in Tables 4 and 5.

Table 4. N-gain Score Criteria

N-gain Value	Improvement Category
< 30%	Low
30% - 70%	Medium
> 70%	High

(Source: Sundayana, 2014)

Table 5. Interpretation of N-gain Effectiveness

N-gain Percentage	Interpretation
< 40%	Ineffective
40% – 55%	Less effective
56% – 75%	Moderately effective
> 76%	Effective

(Source: Hake, 1999)

Result and Discussion

Research Findings

1. *Feasibility Test Results*

The feasibility test results include the evaluation of science teaching materials based on a STEM-integrated Project-Based Learning (PjBL) model, teaching modules, student worksheets, scientific literacy test instruments, and critical thinking test instruments.

The validation results for all developed instruments and products indicate a very high level of validity and are categorized as reliable, with a mean (±SD) validity score of 0.914 (±0.043) and a Percentage of Agreement (PA) of 94.30%. Thus, all developed instruments and products are considered feasible for use in the learning process. The detailed validation results are presented in Table 6.

Table 6. Validation and Reliability Results of All Products

Product	Mean V	SD	PA (%)	Validity Category	Reliability Category
Teaching materials	0.91	0.071	95.77%	Very valid	Reliable
Teaching module	0.90	0.023	94.44%	Very valid	Reliable
Student worksheets	0.94	0.029	95.55%	Very valid	Reliable
Scientific literacy test instrument	0.95	0.046	94.09%	Very valid	Reliable
Critical thinking test instrument	0.87	0.046	91.63%	Very valid	Reliable
Average	0.914	0.043	94.30%	Very valid	Reliable

2. *Practicality Test Results*

The practicality test was conducted to determine the ease of use and implementation of the teaching materials in the learning process. Practicality was assessed through observations of learning implementation and questionnaires on student and teacher responses to the developed materials.

The observation results indicate that the learning process was implemented in the very good category, with a mean (±SD) score of 93.75% (±0.436). This shows that the learning activities were carried out optimally, with relatively small variations in scores across meetings. The details are presented in Table 7.

Table 7. Observation Results of Learning Implementation

Meeting	Mean	SD	Percentage (%)	Category
Meeting I	3.80	0.410	95.00%	Very good
Meeting II	3.65	0.489	91.25%	Very good
Meeting III	3.80	0.410	95.00%	Very good
Average	3.75	0.436	93.75%	Very good

Furthermore, the results of teacher responses show that the STEM-integrated PjBL science teaching materials are considered very practical and suitable for

use in learning, with a mean (±SD) of 96.43% (±0.26), categorized as very practical. The summary is presented in Table 8.

Table 8. Teacher Response Questionnaire Results

Aspect	Mean	SD	Percentage	Category
Design and attractiveness	3.75	0.35	93.37%	Very practical
Teaching effectiveness	3.90	0.14	97.50%	Very practical
Readability and visual	3.70	0.22	92.50%	Very practical
Language	3.75	0.35	93.75%	Very practical
Average	3.86	0.26	96.43%	Very practical

In addition, the practicality of the teaching materials was also assessed based on student responses as direct users in the learning process. The results indicate that the STEM-integrated PjBL science teaching materials are considered very practical and appropriate for use, with a mean (±SD) of 90.90% (±0.45), categorized as very practical. The detailed results are presented in Table 9.

Table 9. Student Response Questionnaire Results

Aspect	Mean	SD	Percentage	Category
Design and attractiveness	3.81	0.39	95.24%	Very practical
Learning engagement	3.74	0.44	93.57%	Very practical
Visual & language	3.51	0.51	87.76%	Very practical
Average	3.64	0.45	90.90%	Very practical

3. Effectiveness Test Results

The science teaching materials based on a STEM-integrated Project-Based Learning (PjBL) model were proven to be effective in improving students' scientific literacy and critical thinking skills. This is evidenced by the results of measurements conducted on 42 students of class VIII-A at SMPN 6 Mataram through pre-test and post-test assessments.

In terms of scientific literacy, the mean (±SD) pre-test score was 45.12 (±6.22), with a range of 30–60, which increased significantly in the post-test to 88.21 (±6.80), with a range of 75–100. The N-gain score obtained was 0.79 (79%), categorized as high with an effective interpretation. Similarly, in terms of critical thinking skills, the mean (±SD) pre-test score was 51.11 (±4.64), with a range of 43–60, which increased to 88.17 (±4.55), with a range of 80–97 in the post-test. The N-gain score was 0.76 (76%), also categorized as high with an effective interpretation.

These findings indicate that the implementation of science teaching materials based on a STEM-integrated Project-Based Learning model is not only capable of improving scientific literacy but also enhancing critical thinking skills, making it effective in supporting science learning oriented toward 21st-century competencies. Furthermore, a comparison of the improvements in students' scientific literacy and critical thinking skills is presented in Figure 1.

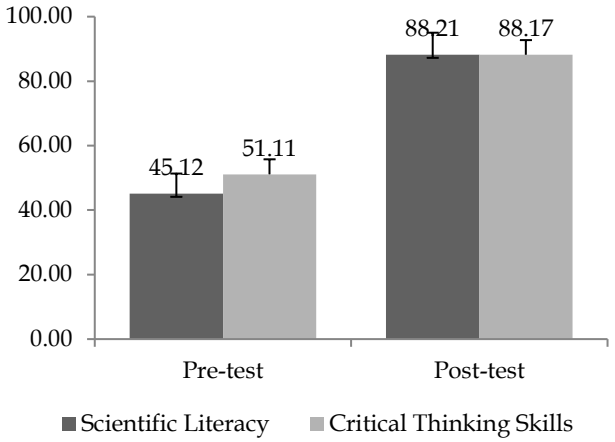


Figure 1. Comparison of the Mean Pre-Test and Post-Test Scores of Students' Scientific Literacy and Critical Thinking Skills. Error Bars Represent 1 SD.

Furthermore, a more in-depth analysis was conducted on the improvement of students' abilities based on each scientific literacy competency and critical thinking skill after participating in learning using science teaching materials based on a STEM-integrated Project-Based Learning model. This analysis aims to identify the patterns of students' ability development in a more specific and comprehensive manner.

Based on the results of the competency-based analysis, it can be concluded that learning using science teaching materials based on a STEM-integrated Project-Based Learning model is effective in comprehensively improving students' scientific literacy and critical thinking skills.

4. Practicality Test Results at the Dissemination Stage of Product Development

The product dissemination was carried out through implementation at SMPN 2 Mataram, particularly in class VIII-F consisting of 40 students. The results of the analysis of student responses to the teaching materials indicate that the STEM-integrated PjBL-based science teaching materials are considered very practical and appropriate for use in learning, with a mean (±SD) of 92.29% (±2.52). The summary of student responses to the teaching materials is presented in Table 10.

Table 10. Student Responses to the Teaching Materials

Aspect	N	Mean	SD	Percentage	Category
Design and attractiveness	40	14.65	0.94	91.56%	Very practical
Learning engagement	40	18.23	0.99	91.15%	Very practical
Visual and language	40	18.73	0.84	93.65%	Very practical
Average		51.61	2.52	92.29%	Very practical

In addition, two science teachers completed the teacher response questionnaire to evaluate the quality of the teaching materials. The results of the analysis indicate that the STEM-integrated PjBL-based science teaching materials are considered very practical and appropriate for use in learning, with a mean (±SD) of 97.32% (±0.20). The summary of teacher responses is presented in Table 11.

Table 11. Teacher Responses to the Teaching Materials

Aspect	Mean	SD	Percentage	Category
Design and attractiveness	4.00	0.00	100.00%	Very practical
Teaching effectiveness	3.90	0.22	97.50%	Very practical
Readability and visual	3.90	0.22	97.50%	Very practical
Language	3.75	0.35	93.75%	Very practical
Average	3.89	0.20	97.32%	Very practical

Discussion

The discussion in this study aims to address the research problems concerning the feasibility, practicality, and effectiveness of science teaching materials based on a STEM-integrated Project-Based Learning (PjBL) model in improving students' scientific literacy and critical thinking skills.

The results indicate that the developed products consisting of teaching materials, teaching modules, student worksheets, and assessment instruments have met the criteria of being highly valid and reliable based on expert judgment, very practical based on implementation observations and teacher and student responses, and effective based on significant improvements in scientific literacy and critical thinking skills. These findings confirm that the developed product is not only theoretically sound but also functionally effective in real classroom contexts.

Conceptually, these results can be explained by the integrated design of the product, where objectives, project activities, and assessments are aligned within a coherent system. The explicit integration of PjBL–STEM in the teaching modules and LKPD encourages students to engage in authentic problem-solving that requires the simultaneous application of science, engineering, technology, and mathematics concepts. This condition is consistent with findings by Afriana et al. (2016), Utami et al. (2020), and Eny & Syahmani (2025), which report that PjBL–STEM effectively enhances scientific literacy by providing contextual and real-world learning experiences. The similarity of these findings lies in the structured project design, explicit interdisciplinary integration, and authentic assessment that measures scientific reasoning, enabling students not only to understand concepts but also to apply them in contextual situations (OECD, 2019).

The effectiveness in improving critical thinking skills is also consistent with studies by Tafakur et al. (2023) and Zhang & Ma (2023), which state that project-based learning significantly enhances analytical, evaluative, and inferential abilities, as students are actively involved in investigation, solution testing, and reflection. The highest improvements in explanation and self-regulation competencies in this study can be attributed to project presentations, group discussions, and structured reflection activities, which provide opportunities for students to articulate ideas and independently monitor their thinking processes, as emphasized by Facione (2011) and Zarouk et al. (2020).

However, some studies report different results, particularly when STEM integration is implemented partially or without clear guidelines (Siew & Ambo, 2018; Santhosh et al., 2023). These differences are generally caused by a lack of coherence among project design, materials, and assessment, resulting in less holistic learning. Additionally, the relatively lower achievement in scientific decision-making found in this study aligns with Pratama et al. (2025), who argue that this competency develops more slowly as it requires multi-perspective evaluation, ethical considerations, and synthesis of information from various sources. Thus, variations across studies are more influenced by the quality of design, teacher readiness, and implementation consistency rather than the PjBL–STEM model itself.

In line with this, the study contributes theoretically by strengthening empirical evidence that the development of science teaching materials based on a STEM-integrated PjBL model validated by experts, systematically designed, and supported by authentic assessment can improve scientific literacy and critical thinking skills. Practically, these findings highlight the importance of developing integrated, contextual, and coherent teaching materials as a strategy to meet 21st-century competency demands in science learning.

These practical implications are further supported in the dissemination stage, which shows that the STEM-integrated PjBL-based science teaching materials

implemented at SMPN 2 Mataram received very practical responses from both students and teachers.

In general, students rated the teaching materials as very practical across all indicators, including design and attractiveness, learning engagement, and visual and language aspects, with overall percentages in the very high category. The participating science teachers also rated the materials as very practical in terms of design, teaching effectiveness, readability, visual presentation, and language. These findings address the research problem at the dissemination stage, demonstrating that the developed product is not only theoretically feasible and effective during the trial phase but also highly acceptable when implemented in different school contexts.

The high level of acceptance can be interpreted as a result of the consistency of the instructional design developed during the design and development stages. The integration of projects with science, technology, engineering, and mathematics components is explicitly structured in the teaching modules and LKPD, enabling students to follow learning activities systematically. This aligns with Afriana et al. (2016), who found that STEM-integrated PjBL enhances student engagement and understanding when projects are contextual and well-structured. The similarity lies in positioning projects as the core of learning while linking them to real-world problems, making learning activities relevant to students' daily lives. This finding is also consistent with Kelley and Knowles (2016), who emphasize that the effectiveness of STEM implementation depends on clear interdisciplinary integration and coherent instructional design.

Moreover, the high response in visual and language aspects indicates that the quality of material presentation plays an important role in enhancing student engagement. This is in line with Delgado et al. (2018), who found that teaching materials with clear textual structure and appropriate visual support can deepen students' conceptual understanding. This similarity can be explained by the systematic presentation of materials using communicative language and relevant illustrations, which helps manage students' cognitive load effectively.

On the other hand, some studies report different outcomes when PjBL–STEM implementation is not supported by detailed guidelines or when teachers are not yet familiar with integrative approaches, leading to less optimal learning implementation (Siew & Ambo, 2018; Santhosh et al., 2023). These differences are generally influenced by variations in implementation quality, teacher readiness, and learning environment support. Therefore, the high practicality observed in this study can be understood as a logical consequence of a product design that has undergone validation, revision, and phased trials before dissemination.

Although the dissemination stage shows very positive acceptance, this study has limitations, as the implementation was conducted in only one partner school with a limited number of respondents. Therefore, broader generalization requires further testing in wider contexts. Nevertheless, this study provides an important contribution to the field of science education development by strengthening empirical evidence that systematically designed, validated, and contextual STEM-integrated PjBL teaching materials can be widely implemented with a very high level of acceptance.

Conclusion

Based on the results of the development research on science teaching materials using a STEM-integrated Project-Based Learning model, it can be concluded that the developed product has empirically met the criteria of feasibility, practicality, and effectiveness. The validation results indicate that the teaching materials are appropriate for use in the learning process, while the trial results show that the product is practical for teachers to implement and can be effectively used by students. Furthermore, the implementation of the teaching materials has been proven to be effective in improving students' scientific literacy and critical thinking skills. Therefore, science teaching materials based on a STEM-integrated Project-Based Learning model can be recommended as an innovative alternative in science learning that supports active, contextual, and sustainable development of 21st-century competencies.

Acknowledgments
Acknowledgments are expressed by the researchers to the team so that researchers can complete research in the form of journal publications.

Author Contributions
All authors contributed to writing this article.

Funding
This research was funded by the Directorate of Research, Technology, and Community Service (DRTPM), Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through the Master's Thesis Research (PTM) grant scheme for Fiscal Year 2025. The author expresses his gratitude for the financial support provided so that this research can be carried out properly.

Conflicts of Interest
No conflict interest.

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