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The Effectiveness of STEM-Based Problem-Based Learning in Enhancing Students' Scientific Argumentation Skills in Respiratory System Learning

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ABSTRACT
Scientific argumentation is a crucial competency in 21st-century science education; however, students' abilities in constructing structured arguments remain limited. This study aims to examine the effectiveness of STEM-based Problem-Based Learning (PBL) in enhancing students' scientific argumentation skills in respiratory system learning. A quasi-experimental design with a pretest–posttest control group was employed. The sample consisted of 70 eleventh-grade students divided into experimental and control groups. Data were collected using a scientific argumentation test based on Claim, Evidence, Reasoning, and Rebuttal (CERR) indicators, observation sheets, and student response questionnaires. Data analysis included N-gain, normality and homogeneity tests, and independent samples t-test. The results indicate a significant improvement in students' scientific argumentation skills in the experimental group compared to the control group. Additionally, students' learning activities and responses were categorized as very good. These findings suggest that STEM-based PBL is an effective instructional approach for improving scientific argumentation skills and promoting active engagement in science learning.

INTRODUCTION

The growing demand for 21st-century competencies has positioned scientific argumentation as a central outcome in science education, particularly in disciplines such as biology where conceptual understanding must be justified through evidence-based reasoning. Scientific argumentation enables students to construct claims, evaluate evidence, and articulate reasoning in addressing complex scientific phenomena. However, empirical evidence consistently indicates that students' argumentation skills remain underdeveloped, especially in structured components such as rebuttal and reasoning. Studies on classroom practices reveal that students often struggle to produce coherent written arguments and tend to rely on superficial explanations rather than evidence-based justification (Evagorou et al., 2023). This issue is further exacerbated by

instructional materials and pedagogical practices that insufficiently support the construction of arguments, as observed in biology learning contexts, such as the respiratory system (Rosliana & Suyanto, 2022). Consequently, the persistent gap between expected competencies and actual student performance underscores the urgency of developing instructional approaches that explicitly foster scientific argumentation within authentic learning environments.

Recent literature has increasingly emphasized the effectiveness of inquiry-oriented and problem-centered pedagogies in enhancing students' argumentation skills. Problem-Based Learning (PBL), for instance, has been widely recognized as a robust approach for engaging students in authentic problem-solving processes that require justification and reasoning. Empirical findings demonstrate that PBL enriched with argument mapping and online laboratory environments significantly improves students' scientific argumentation by facilitating structured reasoning and evidence use (Jumadi et al., 2021). Similarly, the integration of flipped classroom strategies within PBL contexts has been shown to enhance the quality of students' arguments by promoting active engagement and deeper conceptual processing (Putri et al., 2023). Beyond PBL, argument-driven inquiry and metacognitive scaffolding approaches have also demonstrated strong effects on argumentation and higher-order thinking skills, indicating the importance of explicit instructional support in developing argumentative competence (Satriya & Atun, 2024; Marthaliakirana et al., 2022; Anazifa et al., 2024). Moreover, scaffolding strategies in biology learning contexts play a crucial role in supporting students' ability to construct theoretical and hypothetical arguments (Weng et al., 2017). These findings collectively suggest that argumentation can be effectively developed through pedagogical models that integrate inquiry, scaffolding, and active student engagement.

In parallel, STEM education has emerged as a transformative framework that integrates multiple disciplines to enhance problem-solving, critical thinking, and real-world application of knowledge. STEM-based learning environments have been shown to significantly improve students' academic achievement, creativity, and reflective thinking through interdisciplinary engagement (Hasançebi et al., 2021; Hiğde & Aktamış, 2022). When combined with PBL, STEM integration further strengthens students' ability to approach problems holistically and develop evidence-based reasoning. Empirical studies indicate that integrated STEM-PBL models effectively enhance critical thinking and learning outcomes across science domains (Tairas et al., 2024; Ata et al., 2023). Additionally, the use of virtual simulations and authentic problem contexts within PBL-STEM frameworks has been found to significantly improve students' scientific argumentation skills (Permana et al., 2023; Jewaru et al., 2023). These findings align with broader conceptualizations of STEM as an interdisciplinary approach that connects knowledge with real-world applications, thereby fostering deeper understanding and transferable skills (Tillinghast et al., 2020; Guo & Tang, 2021). Thus, the integration of STEM within PBL represents a promising direction for enhancing both cognitive and argumentative competencies.

Despite these advancements, several critical gaps remain in the existing body of research. First, while numerous studies have confirmed the effectiveness of PBL and STEM independently, limited research has systematically examined their integrated impact specifically on scientific argumentation as a multidimensional construct. Second, prior studies often emphasize general learning outcomes such as achievement and critical thinking, with insufficient attention to the detailed components of argumentation, including claim, evidence, reasoning, and rebuttal. Third,

existing research frequently overlooks contextual specificity, particularly in biology education topics where conceptual complexity requires structured argumentative reasoning. Furthermore, challenges identified in argumentation research—such as the difficulty of supporting students in constructing high-quality arguments and the lack of consistent instructional frameworks—remain unresolved (Henderson et al., 2018). These limitations indicate a clear need for a comprehensive instructional model that integrates PBL and STEM and explicitly targets the development of scientific argumentation within specific disciplinary contexts.

Addressing these gaps, the present study proposes an integrated STEM-based Problem-Based Learning approach designed to enhance students' scientific argumentation skills in biology education. This study distinguishes itself by combining interdisciplinary STEM principles with problem-based inquiry while explicitly focusing on the structural components of argumentation. Empirical evidence supports the potential of this integrated approach, demonstrating its effectiveness in improving argumentation skills through authentic, collaborative, and technology-supported learning environments (Muspiroh et al., 2024). By situating the study within respiratory system learning, this research further contributes to subject-specific pedagogical innovation and addresses the need for contextualized instruction in argumentation. Therefore, the objective of this study is to examine the effectiveness of STEM-based PBL in improving students' scientific argumentation skills, to analyze differences between experimental and control groups, and to evaluate students' responses to the implemented learning model. It is hypothesized that integrating STEM into PBL will result in significantly greater improvements in students' argumentation skills compared to conventional instruction, thereby contributing both theoretically and empirically to the advancement of science education.

METHOD

Research Design

This study employed a quasi-experimental design using a pretest–posttest control group structure to examine the effectiveness of STEM-based Problem-Based Learning (PBL) in enhancing students' scientific argumentation skills. This design is widely recognized in educational research as appropriate when random assignment is not feasible while still enabling causal inference through group comparison. Quasi-experimental approaches allow researchers to investigate instructional interventions within authentic classroom contexts, thereby preserving ecological validity while maintaining analytical rigor (Khattib & Alt, 2024). In addition, prior studies have demonstrated that quasi-experimental frameworks are effective for evaluating learning innovations and conceptual understanding in science education settings (Hmelo-Silver et al., 2017). The selected design aligns with the objective of identifying statistically significant differences in argumentation skills between students exposed to STEM-based PBL and those receiving conventional instruction.

Participants

The participants consisted of 70 eleventh-grade students from a public senior high school, selected using a purposive sampling technique based on class equivalence and accessibility. The sample was divided into two groups: an experimental group (n = 35) and a control group (n = 35). The experimental group received instruction through STEM-based PBL, while the control group was taught using conventional methods. This sampling approach is consistent with quasi-

experimental research practices, where intact classroom groups are maintained to ensure the feasibility and authenticity of intervention studies in educational contexts (Khattib & Alt, 2024). All participants had comparable prior knowledge in biology and had not previously experienced integrated STEM-PBL instruction, ensuring baseline equivalence before treatment implementation.

Instruments / Data Collection

Data were collected using multiple instruments designed to capture both cognitive outcomes and learning processes. The primary instrument was a scientific argumentation test administered as pretest and posttest, developed based on the Claim–Evidence–Reasoning–Rebuttal (CERR) framework to assess students' ability to construct structured arguments. The use of pretest–posttest instruments is essential in quasi-experimental designs to measure learning gains and control for initial differences between groups (Zientek et al., 2016).

In addition, an observation sheet was used to document students' learning activities during the intervention, focusing on engagement in problem-solving, collaboration, and argument construction. A student response questionnaire was also administered to capture perceptions of the learning process. All instruments underwent content validation through expert judgment, followed by empirical testing to establish validity and reliability, including item analysis and internal consistency measures. This multi-instrument approach ensures data triangulation and strengthens the robustness of the findings.

Procedure

The research procedure consisted of three sequential phases: preparation, implementation, and evaluation. During the preparation phase, instructional materials and research instruments were developed and validated. The learning design integrated STEM principles into the PBL framework, emphasizing real-world problem scenarios related to the respiratory system. In the implementation phase, the experimental group participated in STEM-based PBL through structured stages: (1) problem orientation, (2) group organization, (3) guided investigation integrating interdisciplinary STEM concepts, (4) presentation of solutions, and (5) evaluation of the inquiry process. The control group received conventional instruction characterized by teacher-centered delivery. This structured intervention approach aligns with established practices in quasi-experimental classroom studies, in which instructional treatments are systematically applied to evaluate their impact on learning outcomes (Hmelo-Silver et al., 2017). The intervention was conducted over several instructional sessions to ensure adequate exposure and engagement in learning. In the evaluation phase, posttests were administered to both groups, and additional data were collected through observation and questionnaires to support comprehensive analysis.

Data Analysis

Data analysis involved both descriptive and inferential statistical techniques. Descriptive statistics were used to calculate mean scores and percentage distributions of students' argumentation skills across the four components: claim, evidence, reasoning, and rebuttal. Inferential analysis included prerequisite tests of normality and homogeneity, followed by an independent samples t-test to compare mean gain scores between the experimental and control groups. The use of this statistical approach is appropriate for pretest–posttest control group designs, provided that underlying assumptions are met, as emphasized by Zientek et al. (2016). The significance level was set at $\alpha = 0.05$. Furthermore, normalized gain (N-gain) analysis was

conducted to determine the magnitude of improvement in students' argumentation skills. This combination of statistical techniques ensures a rigorous evaluation of the effectiveness of STEM-based PBL in improving learning outcomes.

Ethical Considerations

Ethical standards were maintained throughout the study. Prior to data collection, informed consent was obtained from participants and permission was secured from the school authorities. Participants were assured of confidentiality and anonymity, and all data were used exclusively for research purposes. The study adhered to academic integrity standards by ensuring proper citation of all referenced sources and avoiding plagiarism.

RESULTS

Students' Learning Activities in STEM-Based PBL Implementation

Students' learning activities during the implementation of STEM-based Problem-Based Learning (PBL) were measured using an observation sheet aligned with the procedural stages described in the method section. The results are presented in **Figure 1**.

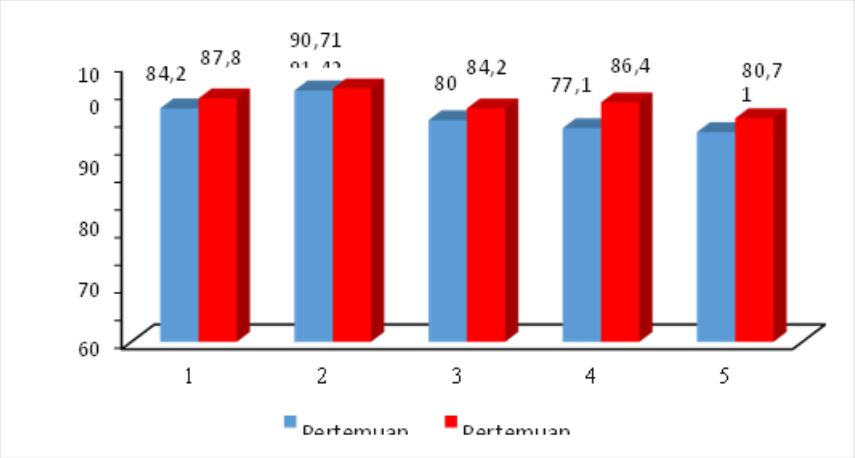

Figure 1. Students' Learning Activities Across PBL-STEM Indicators

The data indicate that students' learning activities improved across all observed indicators from the first to the second meeting. The highest achievement in both sessions was consistently found in **organizing students in learning (Indicator 2)**, reaching 90.71% in the first meeting and increasing to 91.42% in the second meeting. This suggests that collaborative learning structures within STEM-based PBL effectively facilitated student engagement. Conversely, the lowest scores were observed in **the evaluation and reflection processes (Indicator 5), although these also improved** from 75.71% to 80.71%. This pattern indicates that while students actively participated in problem-solving and discussion phases, higher-order evaluative thinking required further reinforcement. To strengthen the interpretation, the aggregated results are summarized in **Table 1**.

Table 1. Students' Learning Activities Across Meetings

Indicator	Meeting 1 (%)	Meeting 2 (%)	Category
Problem orientation	84.28	87.85	Very Good

Organizing learning	90.71	91.42	Very Good
Investigation support	80.00	84.28	Very Good
Presentation of results	77.14	86.42	Good–Very Good
Evaluation process	75.71	80.71	Good

Overall, the average activity increased from **81.57% to 86.14%**, as illustrated in **Figure 2**, indicating a consistent improvement in student engagement throughout the intervention.

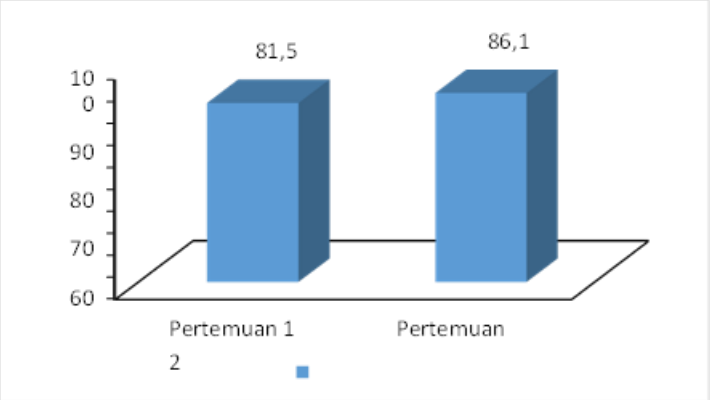

Figure 2. Average Students' Learning Activity Across Learning Sessions

This finding confirms that the structured stages of STEM-based PBL—problem orientation, investigation, and collaborative reasoning—effectively promote active learning behaviors.

Improvement of Scientific Argumentation Skills

Students' scientific argumentation skills were analyzed based on the Claim–Evidence–Reasoning–Rebuttal (CERR) framework. The pretest results are shown in Figure 3

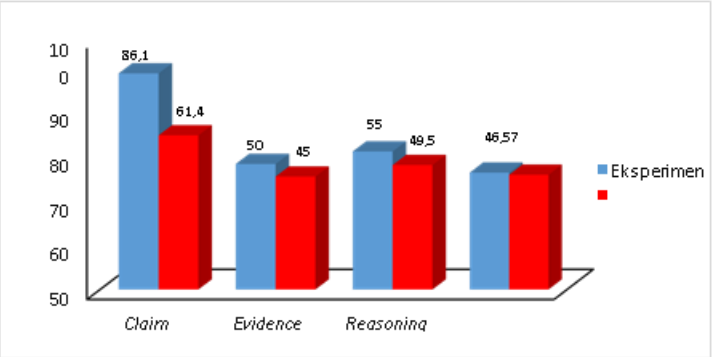

Figure 3. Pretest Mean Scores of Scientific Argumentation Skills Across Indicators

The pretest results reveal that both groups exhibited similar baseline performance, with the highest scores in **claim** and the lowest in **rebuttal**, indicating limited ability to construct counterarguments prior to intervention. Posttest results (Figure 4) demonstrate substantial improvements across all components, particularly in the experimental group.

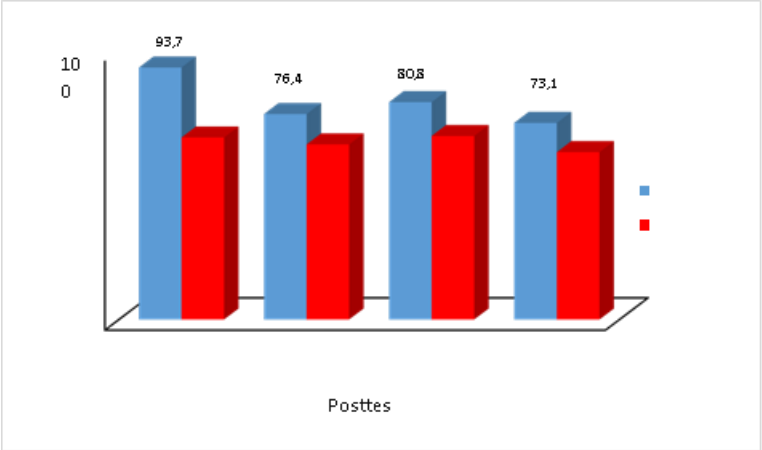

Figure 4. Posttest Mean Scores of Scientific Argumentation Skills Across Indicators

To enhance clarity, the comparison of mean scores is presented in **Table 2**.

Table 2. Mean Scores of Scientific Argumentation Skills

Group	Pretest Mean	Posttest Mean	Category
Experimental	59.39	81.10	Medium → High
Control	50.60	65.82	Medium → Medium

The experimental group showed a significantly higher increase compared to the control group, indicating the effectiveness of STEM-based PBL in enhancing argumentation skills.

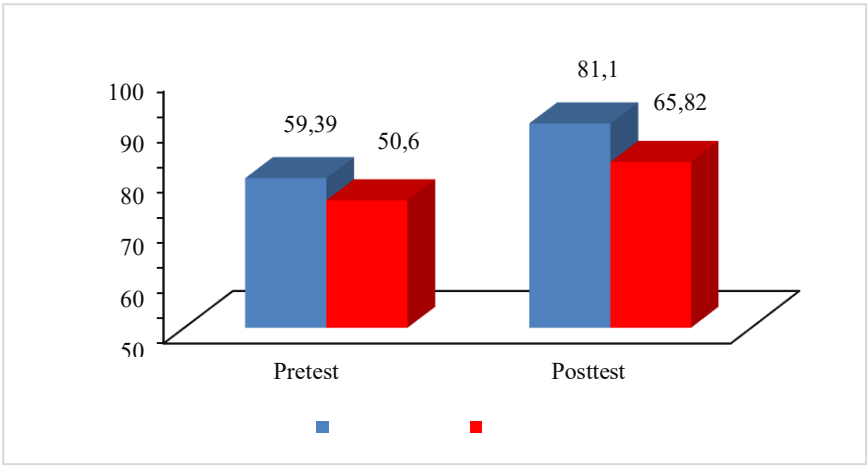

Figure 5. Comparison of Pretest and Posttest Mean Scores Between Experimental and Control Groups

N-Gain Analysis

To determine the magnitude of improvement, normalized gain (N-gain) analysis was conducted.

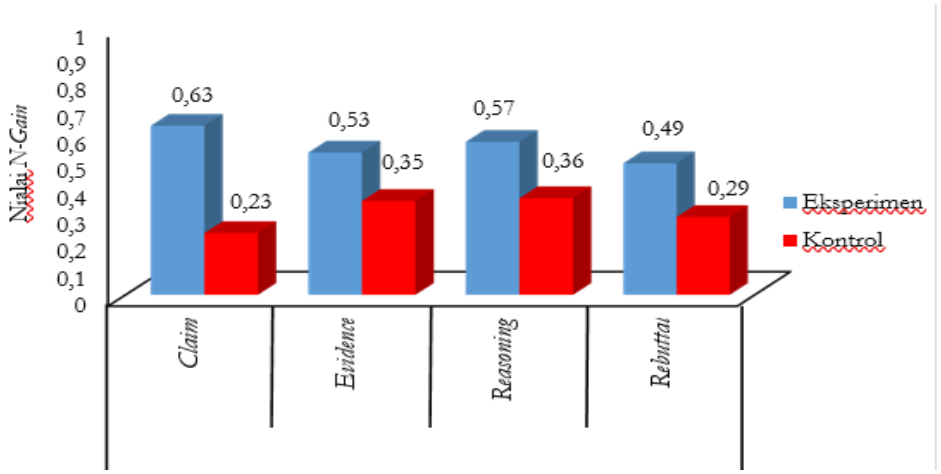

Figure 6. N-Gain Scores of Scientific Argumentation Skills Across Indicators

The results show that the experimental group achieved **moderate improvement across all indicators** (0.49–0.63). The control group showed **lower gains**, particularly in the claim component (0.23). The summary is presented in **Table 3**.

Table 3. N-Gain Scores per Indicator

Indicator	Experimental	Category	Control	Category
Claim	0.63	Moderate	0.23	Low
Evidence	0.53	Moderate	0.35	Moderate
Reasoning	0.57	Moderate	0.36	Moderate
Rebuttal	0.49	Moderate	0.29	Low

Overall N-gain is illustrated in **Figure 7**, where the experimental group (0.53) outperformed the control group (0.30).

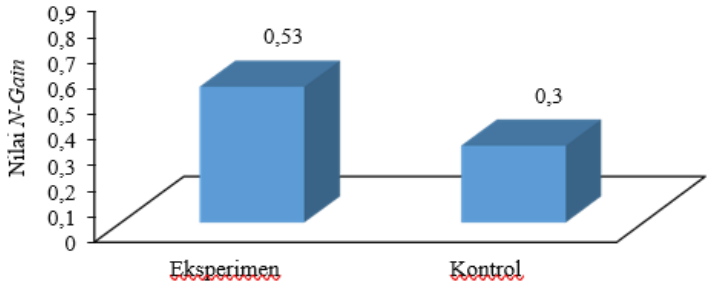

Figure 7. Overall N-Gain Comparison Between Experimental and Control Groups

Inferential Statistical Analysis

Prior to hypothesis testing, normality and homogeneity tests were conducted.

Table 4. Normality and Homogeneity Test Results

Data	Group	Sig.	Interpretation
N-Gain	Experimental	0.200	Normal

N-Gain	Control	0.200	Normal
Homogeneity	Both groups	0.17	Homogeneous

Since all assumptions were met, an **independent samples t-test** was performed.

Table 5. Independent Samples t-Test Results

Variable	t	df	Sig. (2-tailed)
N-Gain	7.818	67	0.000

The results indicate a statistically significant difference (**$p < 0.05$**) between the experimental and control groups. Therefore, the null hypothesis is rejected, confirming that STEM-based PBL has a significant effect on students' scientific argumentation skills.

Students' Responses to STEM-Based PBL

Students' perceptions were measured using a Likert-scale questionnaire.

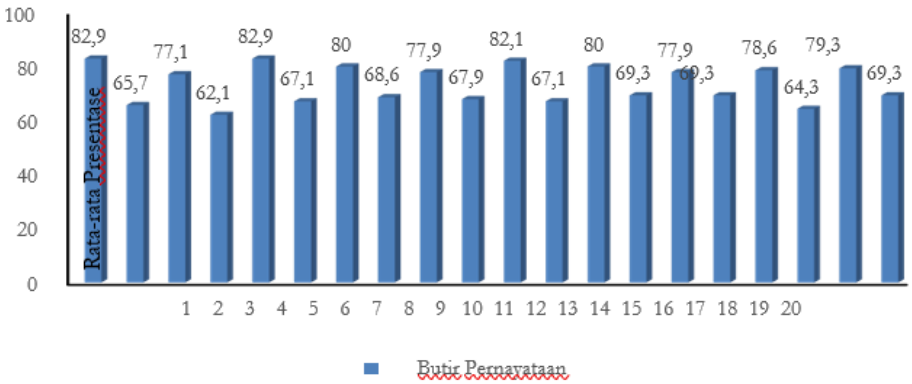

Figure 8. Students' Responses to STEM-Based PBL Implementation

The results show that: Positive responses ranged from 77.1% to 82.9% (very good category). Negative responses ranged from 62.1% to 69.3% (in the good category). To strengthen clarity, the summary is presented in Table 6.

Table 6. Summary of Student Responses

Response Type	Highest (%)	Lowest (%)	Category
Positive	82.9	77.1	Very Good
Negative	69.3	62.1	Good

These findings indicate that students responded positively to STEM-based PBL, particularly due to its emphasis on real-world problem-solving and collaborative learning.

DISCUSSION

The findings of this study demonstrate that the implementation of STEM-based Problem-Based Learning (PBL) significantly enhances students' scientific argumentation skills and learning

engagement. The observed improvement in students' learning activities across instructional sessions indicates that STEM-based PBL creates an active and collaborative learning environment that supports inquiry and reasoning processes. This finding is consistent with prior research emphasizing that problem-oriented and project-based learning environments foster student engagement through authentic tasks and interdisciplinary exploration (Chistyakov et al., 2023; Ragab et al., 2024). The increasing trend of student participation, particularly in collaborative and investigative phases, suggests that structured PBL-STEM stages effectively facilitate meaningful learning experiences. However, the relatively lower performance in evaluative activities indicates that reflective and metacognitive processes require more explicit instructional support.

The improvement in scientific argumentation skills observed in the experimental group further confirms the effectiveness of integrating STEM within PBL frameworks. The significant increase from pretest to posttest scores reflects students' enhanced ability to construct structured arguments involving claims, evidence, and reasoning. This finding aligns with previous studies showing that inquiry-based STEM approaches can stimulate scientific argumentation by engaging students in evidence-based reasoning and problem-solving (Nisa et al., 2023). Similarly, research has demonstrated that PBL modules and structured instructional interventions can significantly improve students' argumentation skills by providing opportunities for discussion, justification, and conceptual clarification (Nurinda et al., 2018; Astriningrum et al., 2024). These results suggest that combining PBL with STEM integration provides a more comprehensive learning environment that supports both conceptual understanding and argumentative competence.

A notable pattern in the findings is the consistent hierarchy among argumentation components, where **claim** achieved the highest scores and **rebuttal** remained the lowest. This pattern indicates that students are more capable of generating initial statements than constructing counter-arguments, which require deeper cognitive processing. This finding is supported by previous studies indicating that students often face challenges in evaluating evidence critically and formulating rebuttals due to the complexity of these skills (Taralli & Skoumios, 2022; Skoumios, 2023). Furthermore, the relatively lower gains in rebuttal suggest that argumentation instruction should move beyond basic claim construction toward fostering dialogical and evaluative reasoning. Research on dialogical argumentation highlights that engaging students in structured argumentative dialogue can significantly enhance their ability to construct evidence-based and counter-arguments (He & Du, 2024). Therefore, while STEM-based PBL effectively develops foundational argumentation skills, additional scaffolding is necessary to strengthen higher-level components such as rebuttal.

The N-gain analysis provides further evidence of the effectiveness of the intervention, showing moderate improvements across all argumentation indicators in the experimental group compared to lower gains in the control group. This result confirms that STEM-based PBL not only improves learning outcomes but also enhances the quality of reasoning processes. The findings are consistent with broader literature indicating that integrated STEM approaches contribute to improved critical thinking and problem-solving abilities through interdisciplinary learning (Mustafa et al., 2016). Moreover, literature reviews on PBL in science education highlight its effectiveness in promoting higher-order thinking skills and meaningful learning by engaging students in real-world problem contexts (Rizal et al., 2023). The moderate gain across evidence

and reasoning components suggests that students were able to connect theoretical knowledge with empirical support, which is a key objective of STEM-integrated instruction.

The statistically significant difference identified through inferential analysis further strengthens the argument that the observed improvements are attributable to the instructional intervention rather than random variation. This finding supports the growing body of evidence that innovative pedagogical models, particularly those integrating inquiry, problem-solving, and interdisciplinary learning, are more effective than conventional instruction in developing higher-order thinking skills. The combination of STEM and PBL appears to create a synergistic effect, where problem-solving contexts enhance conceptual understanding while STEM integration broadens students' perspectives in analyzing scientific phenomena.

In addition to cognitive gains, students' responses indicate a high level of acceptance and positive perception toward STEM-based PBL. The positive responses suggest that students perceive the learning process as engaging, relevant, and meaningful. This aligns with research indicating that interactive and technology-supported STEM learning environments can significantly increase student motivation and engagement (Ragab et al., 2024). The use of real-world problems and collaborative learning structures appears to contribute to a more stimulating classroom atmosphere, which in turn supports deeper learning. These findings highlight the importance of considering affective factors alongside cognitive outcomes in designing effective science instruction. The results of this study confirm that STEM-based PBL is an effective instructional approach for enhancing scientific argumentation skills, particularly in developing claims, evidence, and reasoning. However, the persistent limitations in rebuttal skills indicate the need for more targeted instructional strategies, such as dialogical argumentation and explicit scaffolding, to support higher-level reasoning. Therefore, this study contributes to advancing science education by providing empirical evidence on the effectiveness of integrating STEM and PBL, while also identifying critical areas for future pedagogical improvement.

CONCLUSION

This study demonstrates that integrating STEM principles within a Problem-Based Learning (PBL) framework is an effective instructional approach for enhancing students' scientific argumentation skills. Conceptually, the findings indicate that STEM-based PBL facilitates the development of structured argumentation by engaging students in interdisciplinary problem-solving processes that require formulating claims, using evidence, and constructing logical reasoning. Through this approach, the study addresses the identified problem of students' limited ability to construct scientific arguments by providing a learning environment that actively supports inquiry, collaboration, and evidence-based thinking. From a theoretical perspective, this study advances science education by reinforcing and extending the argumentation framework in inquiry-based learning contexts. The findings support the view that scientific argumentation is not merely an outcome of content mastery but is deeply influenced by the learning environment and instructional design. By integrating STEM and PBL, this study refines existing perspectives on constructivist and inquiry-based learning, demonstrating that interdisciplinary and problem-oriented approaches can strengthen the development of higher-order thinking skills. In particular, the results highlight that while foundational components such as claim and evidence can be effectively developed through structured learning activities, more complex components such as

rebuttal require additional scaffolding, thereby providing a nuanced understanding of how argumentation skills evolve in educational settings. In terms of practical implications, the findings offer valuable insights for educators, curriculum developers, and policymakers. The implementation of STEM-based PBL can be adopted as an alternative instructional strategy to promote active learning and improve students' argumentation skills in science classrooms. Teachers are encouraged to design learning activities that incorporate real-world problems, interdisciplinary perspectives, and collaborative inquiry to foster deeper conceptual understanding. Additionally, the results suggest the importance of explicitly integrating argumentation practices, particularly in guiding students to evaluate and construct rebuttals. At the policy level, these findings support the inclusion of STEM-integrated and inquiry-based approaches in curriculum frameworks to better align educational practices with 21st-century competencies.

Despite its contributions, this study has several limitations that should be acknowledged. The use of a quasi-experimental design with a relatively limited sample size may constrain the generalizability of the findings. Furthermore, the study was conducted within a specific subject context—biology, particularly the respiratory system—which may limit the applicability of the results to other scientific domains. The duration of the intervention was also relatively short, potentially affecting the depth of students' argumentation development, especially in higher-level components such as rebuttal. Future research is therefore recommended to expand the scope and depth of investigation. Subsequent studies may involve larger and more diverse samples, apply longitudinal designs to examine long-term effects, and explore the implementation of STEM-based PBL across different subject areas. Additionally, future research should investigate the integration of explicit scaffolding strategies, such as dialogical argumentation and metacognitive support, to enhance students' ability to construct more sophisticated arguments. Through these efforts, a more comprehensive understanding of how instructional design influences scientific argumentation can be achieved.

ADDITIONAL INFORMATION

Section	Description
Funding	This research received no external funding.
Conflict of Interest	The authors declare no conflict of interest regarding the publication of this paper.
Author Contributions	All authors contributed significantly to this study. Asdarina was responsible for conceptualization, methodology, and writing the original draft. Asep Muhyidin contributed to data collection and analysis. Yudi Juniardi reviewed and edited the manuscript. All authors have read and approved the final version of the manuscript.
Data Availability	The data supporting the findings of this study are available from the corresponding author upon reasonable request.
Ethical Approval	This study was conducted in accordance with ethical research standards. Informed consent was obtained from all participants, and confidentiality of the data was maintained. Ethical approval was obtained from the relevant institutional authority where applicable.

AI Usage Statement	The authors declare that artificial intelligence (AI) tools were used only to assist in language refinement and grammatical editing. All conceptual development, data analysis, interpretation, and scientific conclusions were conducted solely by the authors. The authors take full responsibility for the content and integrity of this manuscript.

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