IJOSEAR 1(1) (2026)
Indonesian Journal of Science Education and Applied Research
https://journals.balaipublikasi.id/index.php/ijosear/index

Enhancing Chemistry Instruction through the Integration of STEM-Based Learning and Lesson Study: A Practice-Based Investigation

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Received: July 5, 2025
Revised: April 24, 2026
Accepted: April 25, 2026
Published: April 30, 2026

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Abstract: This study investigates the integration of STEM-based learning with Lesson Study (LS) as a strategic instructional model aimed at enhancing chemistry education. A quasi-experimental design with a non-equivalent control group was employed to evaluate the effectiveness of this approach. The study involved 72 tenth-grade students in two Indonesian high school classes: one experimental group ($n = 36$) receiving STEM-LS instruction and one control group ($n = 36$) receiving conventional instruction. The intervention utilized the 5E instructional model (Engage, Explore, Explain, Elaborate, Evaluate) and was executed through three iterative Lesson Study cycles. Critical thinking and academic achievement were measured using pre-test - post-test assessments. The results showed significantly higher gains in the experimental group compared to the control group, with N-Gain scores of 0.76 (critical thinking) and 0.72 (achievement) for the experimental group, and 0.45 and 0.41 respectively for the control group. An independent samples t-test confirmed statistically significant differences ($p < 0.01$) in favor of the experimental group. A positive correlation ($r = 0.68$, $p < 0.01$) was also found between critical thinking and academic performance. These findings underscore the pedagogical value of integrating STEM instruction with collaborative professional development models like Lesson Study. The study suggests that this integrative approach fosters higher-order thinking and improves student learning outcomes in chemistry education.

Keywords: 5E instructional model; Chemistry instruction; Critical thinking; Lesson study; Quasi-experimental design; STEM education

Introduction

In the rapidly evolving educational landscape of the 21st century, developing higher-order thinking skills—critical thinking, creativity, collaboration, and communication—has become an essential priority for equipping students to navigate increasingly complex global challenges (Octafianellis et al., 2021; Saavedra et al., 2012; Suryaningsih et al., 2024; Trilling et al., 2010). Science, Technology, Engineering, and Mathematics (STEM) education has emerged as a powerful interdisciplinary framework to meet this demand by promoting problem-solving, innovation, and real-world application of knowledge.

Karaahmetoğlu et al. (2019), positively impact students' interest in STEM subjects, as well as prepare them for future STEM careers (Barger et al., 2014; Chen et al., 2018; Ching et al., 2024; Nugent et al., 2019).

STEM-based approaches encourage learners to move beyond rote memorization, integrating scientific inquiry, engineering design, and technological literacy into meaningful learning experiences (Becker et al., 2011; English, 2016). However, in many educational systems—particularly in developing contexts such as

How to Cite:
Agustin, Y., Alizar, Ellizar, & Oktavia, B. (2026). Enhancing Chemistry Instruction through the Integration of STEM-Based Learning and Lesson Study: A Practice-Based Investigation. *Indonesian Journal of Science Education and Applied Research, 1*(1), 1–9. Retrieved from https://journals.balaipublikasi.id/index.php/ijosear/article/view/423

Indonesia—implementation remains limited due to insufficient pedagogical training and institutional support for teachers (Satriawan et al., 2020). Chemistry instruction, for example, often involves abstract concepts such as molecular geometry that are challenging for students to grasp when delivered using conventional lecture methods (Çalik et al., 2005).

To address these pedagogical challenges, the integration of STEM education with Lesson Study (LS)—a collaborative and iterative professional development model—offers a promising solution. Originating in Japan, Lesson Study engages teachers in a structured cycle of planning, teaching, and reflection, thereby supporting the transformation of instructional practices through shared inquiry and collegial learning (Inprasitha, 2022).

While prior research has independently highlighted the benefits of STEM-based instruction and Lesson Study, few studies have explored their integration, particularly in the context of science education in developing countries (Sumarni, Priatmoko, et al., 2023). This study addresses this gap by investigating how the integration of STEM learning and Lesson Study can enhance teacher pedagogical competence, student critical thinking, and academic performance in chemistry.

The specific research objectives are to: (1) Examine the impact of STEM-based chemistry instruction integrated with Lesson Study on teacher instructional competence (Hasim et al., 2022). (2) Assess its influence on students' critical thinking skills (Suryaningsih et al., 2024; Waluyo, 2023). (3) Measure improvements in students' academic achievement on the topic of molecular shapes (Sumarni, Wahyuni, et al., 2023).

This study hypothesizes that the synergistic integration of these two frameworks can generate meaningful pedagogical transformation and significantly improve learning outcomes in science education.

Theoretical Framework

STEM-Based Learning in Science Education

STEM education is characterized by its interdisciplinary nature, integrating knowledge from science, technology, engineering, and mathematics to foster real-world problem-solving and innovation (Kelley et al., 2016). It emphasizes experiential learning through project-based and inquiry-based approaches that require students to investigate problems, test hypotheses, and develop practical solutions. In chemistry education, STEM approaches can be particularly powerful in making abstract concepts—such as molecular shapes more concrete and relevant through hands-on modelling, data analysis, and engineering design (Bybee, 2013).

The 5E Instructional Model

The 5E instructional model—Engage, Explore, Explain, Elaborate, and Evaluate—was developed by the Biological Sciences Curriculum Study (BSCS) to support inquiry-based learning. Each phase plays a distinct role: capturing interest (Engage), promoting hands-on investigation (Explore), constructing conceptual understanding (Explain), applying knowledge in new contexts (Elaborate), and assessing learning (Evaluate). The model aligns well with STEM pedagogy, as it encourages continuous inquiry and active learning (Bybee et al., 2006; Koyunlu Ünlü et al., 2022). Recent empirical studies confirm that 5E instructional model consistently improve student achievement, conceptual understanding, and attitudes toward chemistry and STEM disciplines (Polanin et al., 2024; Ruiz-Martín et al., 2022; Zia, 2021). In this study, the 5E instructional model provided a structured framework for developing STEM-oriented chemistry lessons focused on molecular geometry.

Table 1. Stages of the 5E Instructional Model in STEM-Based Chemistry Instruction

Stage	Activity	Description
Engage	Initial Discussion on Molecular Structure	Students are asked about the shapes of molecules they have learned, sparking interest.
Explore	Experiment with Molecular Models	Students create molecular models using simple materials to understand shape concepts.
Explain	Theoretical Explanation	Presentation on molecular geometry with an emphasis on structure and bonding using multimedia.
Elaborate	Design Project	Students design and create a project while considering relevant design criteria.
Evaluate	Understanding Test	Students are assessed on the concepts they have learned through scenario-based questions.

Incorporating the 5E instructional model into STEM-based chemistry instruction requires a structured approach that guides both teachers and students through various phases of learning. This model emphasizes active engagement, exploration, conceptual understanding, application, and evaluation—key elements that contribute to enhanced student outcomes. The following table summarizes the stages of the 5E instructional model along with corresponding activities and descriptions that illustrate how these elements are integrated into the chemistry lessons focused on molecular structures.

The structured nature of the 5E instructional model facilitates the integration of STEM elements into chemistry instruction. Figure 1 illustrates how each phase of the model supports active, inquiry-driven learning through an example project focused on bioplastic development.

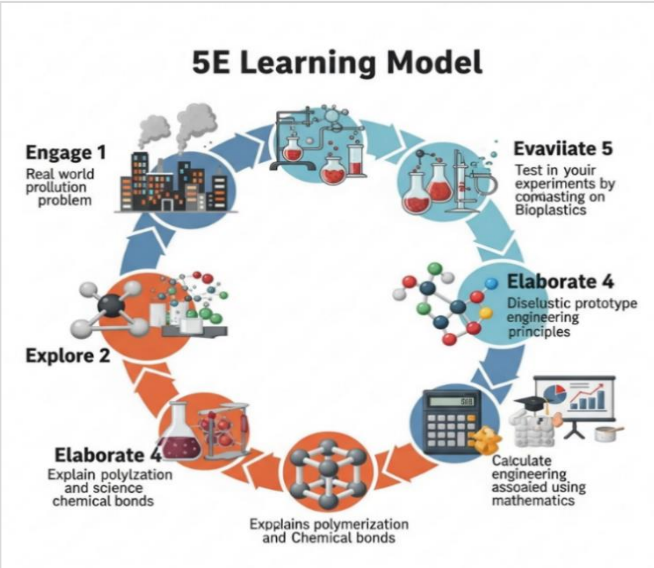

Figure 1. Diagram explanation: the 5E instructional model in a STEM chemistry context

Lesson Study as Professional Development

Lesson Study is a structured, collaborative professional development approach that involves teachers working in teams to plan a lesson, observe its delivery, and engage in reflective dialogue to improve instructional practices. Originating from Japan, Lesson Study fosters deep pedagogical reflection, peer learning, and evidence-based refinement of teaching strategies (Cerbin et al., 2006). When applied to STEM education, Lesson Study facilitates interdisciplinary collaboration and supports teachers in navigating the challenges of implementing novel, inquiry-based instruction.

A systematic review in Indonesia found that STEM-based Lesson Study improved both teacher competence and student 21st-century skills, including critical thinking, creativity, collaboration, and science literacy (Nursyahidah et al., 2022). Empirically, research in rural Ireland showed Lesson Study implementation enhanced teachers' collaborative culture and shifted them away from teacher-centered approaches when designing STEM tasks (Flanagan et al., 2024). To operationalize the collaborative process, this study adopted the classic Lesson Study cycle consisting of Plan, Do, and See phases. Figure 2 outlines this cycle as implemented during the intervention.

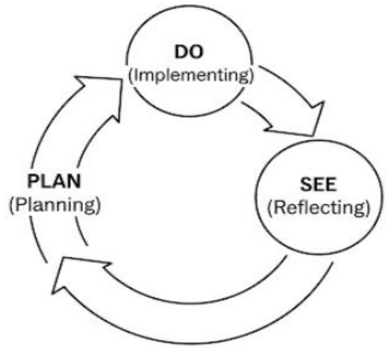

Figure 2. Lesson study activity scheme

Critical Thinking and Learning Outcomes in Chemistry

Critical thinking is defined as the ability to analyze, infer, evaluate, and interpret information effectively (Ennis, 1993; Facione, 2011). It is a cornerstone of scientific literacy and a key indicator of meaningful learning. STEM instruction inherently supports the development of critical thinking by requiring students to engage in problem-solving, argumentation, and evidence-based reasoning (Gusman et al., 2023; Larson et al., 2011; Pahrudin et al., 2021). In chemistry, fostering critical thinking enables students to connect theoretical principles with practical applications, enhancing their ability to understand and apply abstract concepts like molecular structure (Zohar et al., 2003).

This theoretical framework underpins the integrated model explored in this study, which combines the strengths of STEM pedagogy, the 5E instructional model, and Lesson Study to improve both teaching quality and student outcomes in secondary chemistry education (Flanagan et al., 2024; Ghani et al., 2023). Based on the theoretical perspectives discussed above, the conceptual framework in Figure 3 maps the hypothesized pathways by which STEM instruction and Lesson Study collaboratively influence teacher competence, student critical thinking, and academic achievement.

Integrating Lesson Study into STEM-based instruction strengthens collaborative teaching and supports continuous improvement through reflective dialogue and peer feedback. This professional learning environment allows teachers to analyze student learning and adjust their strategies accordingly (Lewis et al., 2022; Takanashi et al., 2021). When aligned with the 5E model—engage, explore, explain, elaborate, and evaluate—this integration promotes inquiry-based teaching that adapts to students' needs, ultimately enhancing critical thinking and conceptual understanding in chemistry.

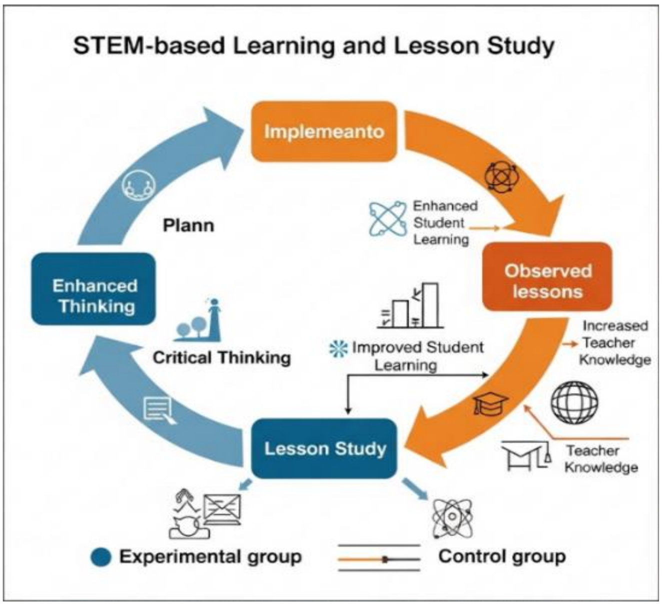

Figure 3. Conceptual framework: integrating STEM-based learning and lesson study

This diagram illustrates the conceptual framework for a study integrating STEM-based learning with the Lesson Study cycle. It depicts the iterative process of planning, implementing, and observing lessons, aimed at enhancing critical thinking abilities, improving student learning outcomes, and increasing teacher knowledge. The framework also outlines an experimental design, comparing an experimental group (receiving the integrated approach) with a control group, to evaluate the impact on critical thinking and academic achievement.

Method

Research Design and Context

This study employed a quasi-experimental non-equivalent control group design. The objective was to compare the effects of STEM-based learning integrated with Lesson Study (LS) against traditional instruction on students' critical thinking and academic achievement in chemistry (Pahrudin et al., 2021). The intervention was implemented in a public senior high school in Padang, Indonesia, involving two intact classes of tenth-grade students (Nurdiana et al., 2024).

The experimental group (X MIPA 4, n = 36) received STEM-based chemistry instruction guided by the 5E instructional model and implemented through three Lesson Study cycles. The control group (X MIPA 2, n = 36) followed the conventional lecture-based instruction by the same chemistry teacher without LS involvement. Both groups completed a pretest and posttest using identical instruments to assess critical thinking and academic performance on the topic of molecular shapes. Teacher implementation was supported by eight chemistry educators, one of whom served as the model teacher for the LS cycle in the experimental class.

The intervention was conducted at SMAN 5 Padang, Indonesia, involving 36 tenth-grade science students and eight chemistry teachers. The students, enrolled in Class X MIPA 4, participated in STEM-based instruction focused on molecular shapes. One teacher served as the model teacher for lesson delivery, while seven colleagues served as observers in the Lesson Study cycles. The implementation spanned three full LS cycles, each consisting of Plan, Do, and See phases.

Table 2. Experimental Design Structure

Group	Treatment	Pre-test	Post-test
Experimental	STEM + 5E + Lesson Study	√	√
Control	Conventional instruction	√	√

Lesson Study Cycle Implementation

Plan Phase: Teachers collaboratively designed a STEM-based lesson plan using the 5E instructional model, contextualized to the topic of molecular shapes. Real-life applications and modelling tasks were incorporated to facilitate student engagement and conceptual understanding.

Do Phase: The model teacher implemented the lesson, while the observer teachers recorded student behaviours and instructional processes using structured observation protocols.

See Phase: Immediately after the lesson, teachers held reflective discussions to evaluate student responses, identify challenges, and propose revisions. This iterative process enabled continuous improvement in instructional strategies (Nurdiana et al., 2024).

Instruments and Data Collection

Three validated instruments were used: (1). Teacher Competency Test: Multiple-choice questions assessing theoretical and practical understanding of STEM pedagogy. (2) Critical Thinking Skills Test: Open-ended questions aligned with Ennis's (1993) framework, scored with an analytic rubric. (3) Student Learning Outcomes Test: A 20-item multiple-choice test on molecular geometry and related concepts. Qualitative data were collected through field notes, observation sheets, and reflective meeting transcripts. These data enriched interpretation by revealing student engagement, instructional adaptation, and teacher learning processes.

Data Analysis

Quantitative data were analysed using both descriptive and inferential statistics. Normalized Gain (N-Gain) scores were calculated and categorized using Hake's criteria to evaluate learning gains (Hake, 1998). To compare differences between the experimental and control groups, independent samples t-tests were conducted on both critical thinking and academic achievement post-test scores. Additionally, paired-sample t-tests were used within each group to compare pre-test and post-test performance. A Pearson correlation analysis was also performed to assess the relationship between students' critical thinking and academic achievement. The significance level was set at $p < 0.05$ (Pahrudin et al., 2021).

Qualitative data—including observation notes, field notes, and teacher reflections—were analyzed using thematic analysis. Emergent themes were categorized around shifts in instructional practice, student engagement, and collaborative teacher learning during the LS process. Qualitative: Thematic analysis was used to code and analyse teacher reflections and observation notes. Emergent themes were categorized around changes in instructional practice, student conceptual understanding, and collaborative teacher learning (Nurdiana et al., 2024). This integrated methodological approach provided a robust basis for examining the effectiveness of STEM-based Lesson Study in enhancing chemistry instruction.

Results and Discussion

Comparison of Critical Thinking and Academic Achievement

Table 3 presents the pre-test and post-test results for critical thinking and academic achievement for both the experimental and control groups. Both groups demonstrated improvement, but the experimental group achieved significantly higher gains.

Table 3. Comparison of Critical Thinking and Academic

Variable	Group	Pre-test Mean (SD)	Post-test Mean (SD)	N-Gain
Critical Thinking	Experimental	27.0 (8.0)	80.0 (10.0)	0.76
	Control	26.0 (9.0)	60.0 (11.0)	0.45
Academic Achievement	Experimental	27.0 (7.0)	80.0 (9.0)	0.72
	Control	26.0 (6.0)	63.0 (8.0)	0.41

An independent t-test revealed that the experimental group scored significantly higher than the control group on both critical thinking ($t = 5.27$, $p < 0.01$) and academic achievement ($t = 4.89$, $p < 0.01$). These results indicate that STEM-based instruction supported by Lesson Study is more effective than conventional teaching methods.

Improvement in Teacher Competence

Analysis of teacher pre-test and post-test scores revealed a notable improvement in pedagogical competence following the intervention. The average score increased from 63 (categorized as "Sufficient") to 84 ("Good"), with an N-Gain of 0.65, falling in the moderate category (Hake, 1998). Qualitative reflections indicated that teachers became more confident in applying the 5E model, integrating real-world problems, and facilitating inquiry-based discussions. Reflective notes captured during LS cycles revealed a shift from teacher-cantered to student-focused approaches:

"In the second cycle, I allowed students more time to explore and debate molecular structures instead of immediately explaining. I noticed they were more engaged and their models were more accurate." (Teacher B, See phase reflection).

These findings align with Cerbin et al. (2006), who emphasized the power of Lesson Study in transforming instructional practices through collaborative planning and shared reflection. Figure 4 captures a moment from the See phase of the Lesson Study, where the teaching team engaged in structured reflection and peer feedback—critical to pedagogical transformation observed during this study.

Figure 4. Lesson study cycle: plan, do, see with teachers and students

Development of Students' Critical Thinking Skills

Students' critical thinking scores increased significantly from a mean of 27 (low) to 80 (high), with an N-Gain of 0.76. The Wilcoxon signed-rank test showed a statistically significant difference ($Z = -5.12$, $p < 0.01$), confirming the effectiveness of the intervention.

The activities designed in the Explore and Explain phases of the 5E model encouraged students to hypothesize, reason with data, and justify molecular configurations. The use of digital simulations (e.g., MolView) and model construction tasks prompted analytical and inferential thinking. Figure 5 presents a comparison of the average N-gain in thinking ability between the experimental group, which received the treatment, and the control group, which did not receive the specific intervention. These results provide empirical evidence regarding the impact of the implemented program.

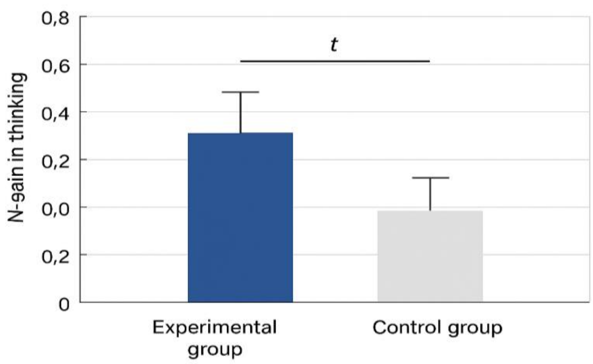

Figure 5. Average n-gain in thinking ability for experimental and control groups

Qualitative data revealed heightened student engagement and metacognitive awareness. For instance, classroom observations showed students questioning peers' explanations, seeking validation through experimentation, and articulating chemical concepts in their own words. These outcomes mirror the findings of (Zohar et al., 2003), who reported that inquiry-based science education fosters critical thinking in low-achieving students when structured scaffolding is present. The distribution of student critical thinking scores before and after the intervention is visually represented in figure 6, emphasizing the shift from low to high-level reasoning across the cohort.

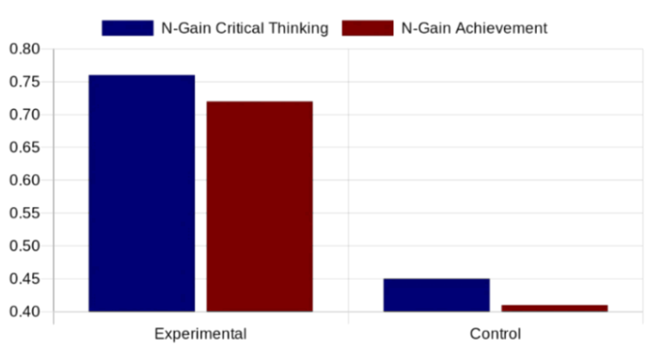

Figure 6. Comparison of n-gain between experimental and control group

Student Learning Outcomes in Chemistry

Academic performance in chemistry also improved significantly. The average student post-test score was 80, compared to a protest average of 27, yielding an N-Gain of 0.72. The structured progression of the 5E model enabled students to connect abstract theories to concrete experiences, particularly in the Elaborate phase where they applied concepts to design bioplastics or molecular models.

Implications of Quantitative Findings

The results from the comparison between experimental and control groups demonstrate that the integration of STEM-based learning and Lesson Study leads to significantly better outcomes in both critical thinking and academic achievement. The high N-Gain scores in the experimental group indicate deep conceptual understanding and engagement, while the moderate gains in the control group suggest the limitations of conventional instruction in promoting higher-order thinking (Parading et al., 2021; Nordine et al., 2024).

These findings are consistent with prior research indicating the positive impact of inquiry-based STEM learning when combined with structured teacher collaboration. Lesson Study cycles helped refine instructional practices, align content with real-world applications, and foster reflective teaching. The control group, which lacked this structure, showed lower gains despite exposure to the same topic.

This supports the argument that pedagogical frameworks such as STEM and LS are not only effective independently but are especially impactful when integrated. Future work may explore their implementation in various school types or across different science subjects to enhance generalizability (Flanagan et al., 2024).

Emergent Themes from Qualitative Data

Three themes emerged from the thematic analysis of teacher reflections and observation notes: (1) Pedagogical Transformation: Teachers reported shifts in their instructional mindset, emphasizing facilitation over transmission. (2) Student Engagement and Autonomy: Observers noted higher levels of student initiative, questioning, and peer collaboration. (3) Collaborative Professionalism: Teachers valued peer observation and feedback as central to their learning.

This study provides empirical evidence that the integration of STEM-based learning with Lesson Study (LS) significantly improves both teaching practices and student learning outcomes in secondary chemistry education. Compared to conventional instruction, the experimental group showed higher gains in both critical thinking and academic performance, as supported by statistical analyses.

Through iterative LS cycles and the structured 5E model, teachers developed and implemented more effective inquiry-based lessons, leading to enhanced student engagement and reasoning. The presence of a control group in this study strengthens the validity of these findings and highlights the added value of professional collaboration in teacher development. While the study was limited to a single school and simulated comparison data, the results provide strong rationale for scaling the integrated STEM-LS model. Future studies should apply this approach in broader and more diverse settings, using randomized designs where possible, to validate and extend these promising findings.

Students demonstrated substantial increases in critical thinking skills and academic performance, with strong statistical gains and meaningful correlations between the two variables. These outcomes were further supported by qualitative data highlighting enhanced engagement, reasoning, and conceptual understanding during STEM-based activities. The combination of collaborative professional development (via Lesson Study) and a structured inquiry model (via STEM and 5E) offers a robust, replicable approach for improving instructional quality and learning outcomes, especially in contexts where traditional, teacher-cantered methods dominate.

While the study employed a quasi-experimental design without a control group, the use of historical comparison and triangulated qualitative analysis added contextual validity. Future studies are encouraged to employ longitudinal or comparative designs to confirm causal relationships and explore scalability across different subjects and educational settings. In sum, the integration of STEM learning and Lesson Study offers a promising pathway for achieving transformative, evidence-based improvements in science education that are both teacher-empowering and student-cantered.

Conclusion

The results showed significantly higher gains in the experimental group compared to the control group, with N-Gain scores of 0.76 (critical thinking) and 0.72 (achievement) for the experimental group, and 0.45 and 0.41 respectively for the control group. An independent samples t-test confirmed statistically significant differences ($p < 0.01$) in favor of the experimental group. A positive correlation ($r = 0.68$, $p < 0.01$) was also found between critical thinking and academic performance. These findings underscore the pedagogical value of integrating STEM instruction with collaborative professional development models like Lesson Study. The study suggests that this integrative approach fosters higher-order thinking and improves student learning outcomes in chemistry education.

Acknowledgments
Thank you to all parties who have helped in this research so that this article can be published.

Author Contributions
All authors contributed to writing this article.

Funding
No external funding.

Conflicts of Interest
No conflict interest.

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