Bridging Theory and Practice: How 3D Learning Transforms STEM Professional Development for Science Teachers' PCK

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Abstract

The ability of science teachers to incorporate STEM-based learning remains limited, substantially affecting the quality of science education. Addressing this gap requires pedagogical skill, particularly in designing context-appropriate instructional materials and assessments. This community engagement project assessed the implementation and impact of a continuous professional development (CPD) programme aimed at enhancing teachers pedagogical content knowledge (PCK) through STEM education. The programme employed a three-dimensional (3D) learning framework to integrate science, technology, engineering, and mathematics in a contextualised, applied approach grounded in deep learning concepts. The intervention consisted of four intensive training modules covering STEM and 3D learning foundations, claim–evidence–reasoning (CER) strategies, CER application in interaction-themed lessons, and CER-based assessment design. Implementation occurred in three phases: preparation, execution, and evaluation. Findings indicate that the programme significantly improved teachers PCK, enabling them to deliver more relevant and innovative science teaching aligned with 21st-century educational expectations. This study highlights the potential of 3D learning–embedded STEM CPD as a transformative model for teacher development, with implications for scalable professional development frameworks in similar contexts.

Keywords: pedagogical content knowledge, STEM education, continuous professional development, 3D learning

Introduction

The primary objective of STEM education is to develop STEM-literate students who can recognise, utilise, and synthesise STEM concepts to address real-world challenges through experiential, inquiry-based learning methods. This vision aligns with international educational priorities that emphasise cultivating capabilities for the 21st century, when technological progress and complex societal issues necessitate innovative, interdisciplinary solutions. In the Indonesian setting, specifically in Karanganyar Regency, the delivery of quality STEM education faces substantial problems that require immediate attention, as indicated by the latest PISA 2022 findings, which show that Indonesian students science

literacy is below international levels. The systemic challenges in the quality and delivery of scientific education necessitate targeted interventions that enhance teacher competence and classroom practices.
This community service programme addresses several converging causes that jeopardise Indonesias educational competitiveness and human resource development. The nations declining STEM competency indicators on international exams indicate a widening gap between Indonesian students and their global counterparts. Secondly, the swift technological progress of Industry 4.0 necessitates that educators cultivate new pedagogical competencies, which many existing professional development programmes inadequately address. Third, in the schools of Karanganyar, a persistent disparity exists between curricular expectations and classroom realities, with conventional teaching methods prevailing despite government initiatives advocating more student-centred, inquiry-based approaches. This scenario reflects broader national patterns in which the implementation of STEM education frequently falters at the conceptual stage, failing to transition effectively into everyday classroom application.

The programmes theoretical contribution lies in its integration of three research -based frameworks adapted for the Indonesian context. The three-dimensional STEM learning approach integrates scientific practices, crosscutting concepts, and disciplinary core ideas, making abstract concepts more comprehensible for both educators and learners. This is augmented by the Claim-Evidence-Reasoning approach, which cultivates scientific argumentation skills and visual modelling tools that facilitate the representation of complex concepts in concrete terms. This project is distinguished from typical training programmes by its focused emphasis on improving Pedagogical Content Knowledge, the vital combination of subject-matter understanding and pedagogical skill deemed necessary for effective teaching, according to studies. This model contrasts with conventional professional development, which typically takes place in isolated workshops, by integrating learning into ongoing mentorship relationships, tailoring to local curriculum requirements, providing practical classroom implementation assistance, and fostering professional learning communities that persist beyond the formal programme duration.

Needs assessments in Karanganyar classrooms identified predominant textbook-based instruction with minimal technology integration or experiential learning. The predominant approach to science education continues to rely on textbooks, with minimal incorporation of existing technologies or experiential learning possibilities. Inquiry-based methods, though present in curriculum documents, are rarely practised, and assessments prioritise rote memorisation over higher-order thinking. These gaps contribute to declining student interest in STEM, persistent gender disparities in participation, and widespread student anxiety regarding science competencies, creating a cycle that limits the regions human resource development. The scenario engenders a detrimental cycle in which insufficient STEM preparation in schools results in diminished STEM participation in higher education and employment, ultimately constraining the regions human resource development and economic potential.

The programme was executed through a structured four-phase plan: diagnostic (needs assessment), capacity-building (hands-on training in 3D Learning, CER, and modelling), implementation support (in-class mentorship), and evaluation (systematic analysis of teaching practices and outcomes). The diagnostic phase commenced with thorough needs assessments via classroom observations and teacher interviews, providing baseline data regarding existing practices and issues. This guided the capacity-building phase, which went beyond traditional seminars to include rigorous, hands-on training in 3D Learning integration, scientific argumentation methodologies, and visual modelling tools. The implementation support phase thereafter offered in-class mentorship as educators began applying these novel methodologies, cultivating professional learning communities and aiding resource development. The evaluation phase methodically examined changes in teaching practices and student learning outcomes, yielding data to enhance and optimise the programme model. The collaborative development of contextualised lesson plans and the establishment of teacher communities suggest impacts extending beyond individual participants. This effort demonstrates that meaningful improvement in STEM education requires comprehensive, practice-oriented support structures for teachers, offering a reproducible framework for enhancing science teacher pedagogical content knowledge in Indonesia and beyond.

Initial findings from the programme indicate its efficacy in revolutionising STEM educational practices in Karanganyar. Participating educators have shown considerable advancement in both confidence and proficiency regarding STEM integration, accompanied by notable enhancements in observed inquiry-based teaching methodologies. The joint development of contextualised STEM lesson plans and the formation of school-based teacher communities indicate that the programmes effects will extend beyond individual participation, fostering systemic improvements. Participant responses regularly underscore the significance of the programmes practical, classroom-relevant methodology, continuous mentorship, and prospects for collaborative planning and resource creation, elements sometimes absent in conventional professional development frameworks.

This community service effort provides persuasive evidence that significant enhancement in STEM education necessitates more than mere curriculum modifications or policy directives; it requires comprehensive, practice-oriented support structures for educators. The programmes 3D learning integration methodology offers a reproducible framework for augmenting science teachers pedagogical content knowledge in analogous contexts throughout Indonesia and beyond. Future targets include institutionalising the established professional learning communities, creating regional STEM teaching resources, promoting legislative support for enduring mentorship programmes, and broadening the effort to include additional schools in the region. Future research should investigate the programmes long-term effects and consider modifications for diverse educational settings, ensuring that all students, regardless of location or background, can access high-quality, effectively delivered STEM education that equips them for the challenges and opportunities of a rapidly changing world.

Problem Statement

An initial assessment of science teachers in Karanganyar Regency reveals significant gaps in the implementation of STEM education. Baseline data indicate that only 62.96% of teachers have prior experience with STEM teaching methods, while 37.03% have never implemented STEM approaches. Teachers demonstrate limited understanding of core STEM integration principles (66.95% proficiency), with pronounced deficiencies in three-dimensional learning application (74.62%), scientific explanation through CER frameworks (69.79%), and interactive lesson design (69.75%). These competency gaps are concentrated in rural schools (72% of teachers lacking STEM experience), exacerbating urban-rural educational disparities.

The limited foundational capabilities of teachers directly affect instructional quality, with classroom observations showing only 28% of lessons effectively incorporating authentic STEM elements. This situation stems from systemic shortcomings in professional development, where previous training programmes have failed to translate into practical teaching competencies. The correlation ($r = .62$) between teacher capability levels and student performance in scientific reasoning underscores the urgent need for targeted interventions to strengthen teachers pedagogical content knowledge and classroom implementation skills for meaningful STEM education reform. These findings highlight the critical need for a comprehensive professional development programme that specifically addresses the identified gaps in teachers STEM pedagogical competencies while considering the contextual challenges of Karanganyars educational landscape.

Objectives

This study aims to design and evaluate a professional development programme to improve the STEM pedagogical competencies of science teachers in Karanganyar Regency, emphasising the reconciliation of theoretical knowledge with classroom application. The objectives are:

1. To design and implement a 3D learning-integrated STEM professional development programme addressing the identified pedagogical deficiencies among science teachers.
2. To assess the programmes efficacy in improving teachers competencies in STEM integration, CER implementation, and interactive lesson design.

Research Questions

1. How significantly does the 3D learning-integrated professional development programme enhance the STEM pedagogical competencies of science teachers in Karanganyar?
2. In what ways does the programme influence educators capacity to apply CER strategies and create engaging STEM lessons?

Literature Review

Effective STEM education requires substantial pedagogical content knowledge, the specialised understanding of how to make STEM concepts comprehensible to students (Shulman, 1986). This is essential for implementing three-dimensional learning that integrates disciplinary core ideas, crosscutting concepts, and scientific practices (NGSS Lead States, 2013). Research consistently indicates that many educators struggle to develop the requisite pedagogical content knowledge for meaningful STEM integration, often due to inadequate preparation programmes and limited opportunities for classroom application (Kind, 2009; Jones et al., 2021).

The issue of developing STEM pedagogical content knowledge shows in several critical areas. Although 72% of Indonesian science instructors report having undergone STEM-related training, classroom observations show that only 28% of lessons demonstrate good STEM integration (Karanganyar Education Office, 2023). This implementation gap indicates that existing professional development methods often fail to translate theoretical knowledge into classroom practice. Secondly, evaluations of teacher competencies reveal notable deficiencies in the integration of engineering design processes (69.79% proficiency) and the development of interactive STEM classes (69.75% proficiency), despite their critical importance to high-quality STEM education (Bybee, 2013). Third, the issue is intensified in rural schools, where 72% of teachers possess limited STEM experience, resulting in considerable equity challenges in access to STEM education.

Research delineates several critical components for developing effective STEM pedagogical content knowledge (PCK). First, enhancement of content knowledge is essential, as educators require a robust conceptual understanding of the interrelationships among STEM disciplines. Insufficient content knowledge has been shown to result in underdeveloped PCK (Kind, 2009), particularly in engineering education, where many teachers are not adequately prepared to integrate engineering principles with science and mathematics (Denson & Lammi, 2014). Second, effective STEM instruction requires appropriate pedagogical strategies for integration, including project-based learning and inquiry-based instruction. The claim–evidence–reasoning (CER) framework has demonstrated its value in developing students' scientific argumentation skills, provided that teachers receive adequate preparation (McNeill & Krajcik, 2011), although existing teacher preparation programmes often emphasise discrete instructional techniques rather than integrated STEM approaches (Capraro et al., 2016). Third, contextual adaptation is a key component of strong PCK, as teachers must be able to tailor STEM concepts to their specific classroom contexts and student needs (Gess-Newsome, 2015), particularly in resource-limited environments where available materials must be used creatively. However, several systemic challenges hinder the development of STEM pedagogical content knowledge, including deficiencies in teacher preparation, as many pre-service programmes continue to focus on discipline-specific training rather than fostering integrative STEM teaching competencies (Honey et al., 2014), limited practical teaching experiences, with relatively few programmes providing sustained classroom implementation support (Love & Wells, 2018), and assessment misalignment, as current evaluation frameworks rarely measure the interdisciplinary PCK required for effective STEM instruction (Correia & Baptista, 2022).

Emerging research suggests promising solutions. Professional development that integrates coursework with supervised classroom application is more effective for pedagogical content knowledge acquisition (Clarke & Hollingsworth, 2002). Professional Learning Communities in which teachers collaboratively develop STEM curricula demonstrate superior implementation quality (Fullan & Langworthy, 2014). Finally, PCK-focused assessment tools like the Content Representation (CoRe) framework help identify and address specific deficiencies (Loughran et al., 2012)

Methodology

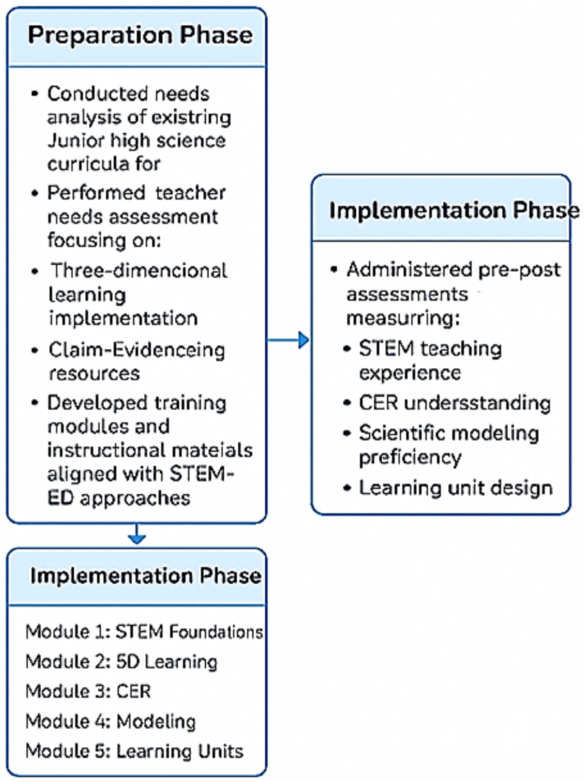
Research design and Participant

This study employed a professional development intervention to enhance science teachers pedagogical content knowledge in STEM instruction through a structured community service programme. The programme was delivered via two workshop sessions on June 19 and July 7, 2025, for the Karanganyar Regency Science Teacher Working Group (MGMP IPA) Cluster 5. The participant pool comprised 35 junior high school science educators. Attendance was 28 for the first session and 26 for the second. Demographic analysis indicated a predominantly female sample (85.2%), with teaching experience ranging from novices to a veteran with nearly thirty years of experience.

The intervention framework adhered to a painstakingly structured three-phase approach to guarantee systematic execution and assessment. In the preparatory phase, the research team conducted a comprehensive needs assessment, evaluating current scientific curricula for alignment with STEM-ED and pinpointing specific deficiencies in teachers competencies. The implementation phase comprised five meticulously organised competency modules delivered through interactive workshops. The STEM Foundations module developed fundamental conceptual understanding, whereas the 3D Learning component emphasised integrating core disciplinary concepts with scientific methodologies. Particular attention was paid to the CER framework for cultivating scientific argumentation skills and the SageModeler apps for conceptual visualisation. The concluding lesson focused on creating interactive learning units and highlighted ways to involve students. Each module integrated theoretical principles with practical classroom applications, enabling participants to apply what they learned in their teaching environments promptly. The qualitative data collection included assessments of lesson plans, observations of workshops, and reflective discussions, yielding detailed insights into pedagogical reform. The programme adhered to a three-phase implementation framework.

Figure 1

The three-phase is a simple stationary mode



The evaluation tools exhibited robust psychometric characteristics, with a 35-item Likert-scale questionnaire reflecting exceptional internal consistency (Cronbachs $\alpha = 0.82$) across all assessed categories. Classroom implementation rubrics and observation protocols supplemented the quantitative data, facilitating the triangulation of outcomes. This multi-method approach for a comprehensive evaluation of knowledge acquisition and practical application ensures that the interventions impact can be meticulously documented and assessed for future programme enhancement. The methodologys rigorous design provides a reproducible framework for analogous STEM PCK development programmes in other educational contexts. Reliability analysis demonstrated robust internal consistency (Cronbachs $\alpha = 0.82$) across all instrument domains. The methodology yielded extensive data on knowledge acquisition and practical application skills arising from the intervention.

Data Analysis and Result

The community service initiative, designed to enhance science teachers pedagogical content knowledge through STEM education-based continuous professional development (STEM-ED CPD), was successfully implemented. The programme commenced with the distribution of pre-questionnaires to assess participants baseline competencies. This activity was conducted on Thursday, 19 June 2025, at SMP Negeri 3 Karanganyar, with a total of 28 participants in attendance. Participants demographic characteristics, including gender, age, and grade levels taught, are presented in Figures 2 and 3.

Figure 2

Demonstration of the sinking and floating phenomenon as a Claim

Figure 3

Evidence-gathering activities by participants

The activities of the first day consisted of three consecutive modules:

1. Introduction to Three-Dimensional STEM Education

   The first 60-minute course acquainted participants with the fundamentals of 3D learning in STEM education. The programme commenced with an evaluation of current statistics on scientific, reading, and mathematics literacy in Indonesia, followed by an analysis of modern science pedagogical approaches. The seminar emphasised problem-solving strategies that replicate the procedures used by scientists, engineers, and mathematicians through 3D STEM learning frameworks. The three elements of learning, such as core disciplinary ideas, cross-cutting concepts, and scientific practices, were comprehensively elucidated. The event ended with an interactive question-and-answer segment.

2. Inquiry-Based Learning: CER Methodology

This 60-minute lesson concentrated on enhancing participants compre hension of CER as essential to scientific practice. The session presented the CER framework, highlighting: (1) the formulation of claims to tackle scientific inquiries via variable relationships, (2) the collection of evidence through scientific data to validate claims, and (3) the development of reasoning to substantiate the evidentiary support while integrating pertinent scientific principles. Participants analysed classroom implementation cases and deliberated on prevalent problems in students applicati on of CER, thereby providing them with methods to enhance students comprehension. The module culminated in a discussion session.

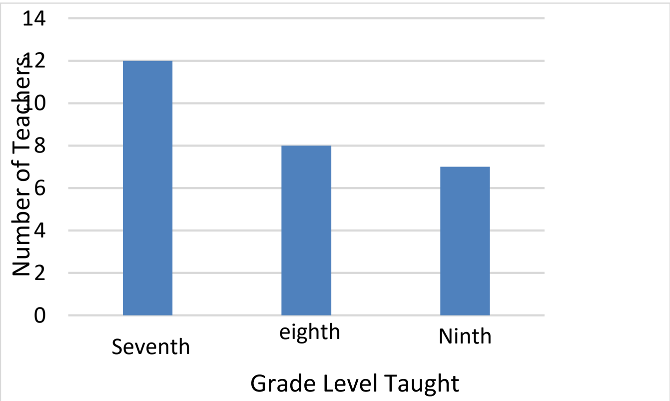
3. Workshop on Scientific Modelling

This 90-minute practical seminar illustrated how to design and apply models to elucidate scientific phenomena. Participants actively used CER by investigating buoyancy principles, first by creating claims about floating and sinking items (Figure 1). The evidence collection phase encompassed experimental design and inquiry (Figure 2), succeeded by model refinement and the formulation of scientific explanations. A thorough analysis of variables, such as the impact of size on buoyancy, strengthened fundamental components of the CER framework. The seminar ended with an extensive discussion.

The systematic execution of these modules effectively included participants in active learning while covering essential elements of STEM pedagogical content knowledge. The sequential approach, advancing from theoretical underpinnings to practical application, enabled significant professional improvement, as demonstrated by participant engagement and post-session ratings. The amalgamation of demographic data collection with focused competency development established a comprehensive framework for evaluating the programmes effect on the increase of instructors pedagogical content knowledge.

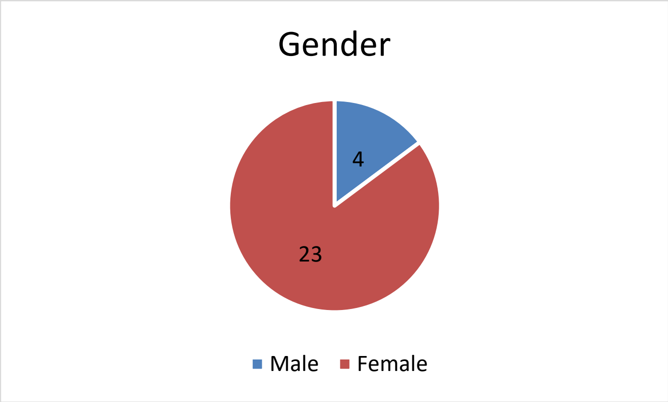
Graph 1

Participant Demographics by Grade Level Taught



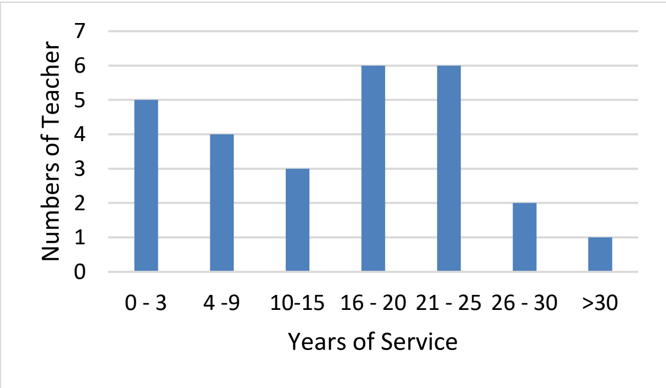
Graph 2

Gender distribution of participants. The graph shows that 4 participants were male and 23 were female.



Graph 3

Distribution of Work Tenure



The community service programme was successfully conducted on 7 July 2025, in the hall of SMP Negeri 2 Karanganyar, with 26 participants in attendance. The programme comprised three structured activities aimed at enhancing teachers pedagogical content knowledge in STEM education.

Activity 1: The Concept of Interaction in Science (30 minutes)

This workshop sought to enhance participants comprehension of interaction phenomena in physics, chemistry, and biology using inquiry-based learning. Four principal units were introduced:

Unit 1: "What causes certain fabrics to adhere when removed from a dryer?" (Relevant to Grade IX (static electricity, electric fields, potential difference), Grade 8 (elements, compounds, mixes), Seventh Grade (scientific investigation, characteristics of materials, ecology))

Unit 2: "In what manner can a minor spark initiate an explosion?" (Applicable to Grade IX (same as Unit 1) and Grade VIII (work, energy, simple machines, elements, compounds, mixtures))

Unit 3: "What are the causes of storms?" (Relevant to Grade VIII (elements, compounds, mixes) and Grade VII (temperature, heat, expansion)).

Unit 4: "What makes a temperature of 107°F (41.7°C) fatal?" Associated with Grade VIII (elements, compounds, mixtures, human life) and Grade VII (properties and transformations of matter)

Activity 2: Modification of Lesson Interaction Units (60 minutes)

Participants collaborated to create lessons centred on driving questions to enhance scientific reasoning. The session had five organised lessons:

Lesson 1: "What occurs during the interaction of objects?" Tasks: Analysing interaction phenomena (attraction/repulsion) through visuals (Figure 3) and simulations, and articulating preliminary assertions.

Lesson 2: "How do scientists comprehend interactions between charged objects?" Tasks: Determining interaction parameters (attraction/repulsion) via video analysis and experimental design.

Lesson 3: "What methods can we employ to examine static electricity interactions?" Engaging in static electricity experiments and data analysis.

Lesson 4: "In what manner does electric charge affect interactions between objects?" Tasks: Assessing variables influencing interactions of charged objects by modelling.

Lesson 5: "What are the applications of electrostatic interaction in everyday life?" Tasks: Designing posters on the practical uses of static electricity and delivering presentations on the findings.

Task 3: Claim-Evidence-Reasoning Evaluation (60 minutes)

This programme instructed participants on evaluating student responses using the CER framework. Essential steps comprised: 1) Presenting a rubric for evaluation based on the CER framework. Upon analysing two sample responses (Figures 4 and 5), it was observed that participants initially assigned a lower rating to Figure 1 than to Figure 2; however, subsequent discussion indicated that both responses lacked comprehensive explanations of the chemical reactions. 2) A question-and-answer session emphasised appropriate CER evaluation practices.

Results of Pre- and Post-Questionnaires

Twenty-six educators completed the pre-questionnaire, while twenty-five completed the post-questionnaire. The data was classified into public (14) and private (8) school educators.

Table 1

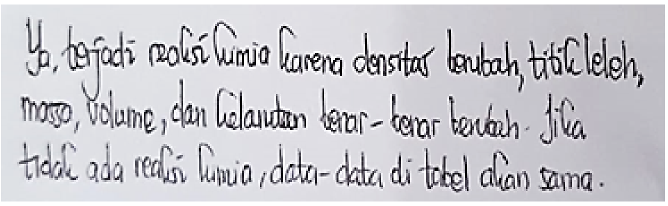
Results of Pre- and Post-Questionnaires

Group	Pre-Activity (%)	Post-Activity (%)
Public Schools	68	72
Private Schools	74	77

Table 1 indicates that both public and private junior secondary school teachers demonstrated improvement from pre- to post-programme evaluations. However, comparative analysis revealed notable differences in outcomes between the two groups. A clear disparity was observed in teachers enthusiasm for using compound -mixing simulations as instructional tools, with private school teachers showing greater receptiveness than their public school counterparts. Overall, improvement was evident in both cohorts, with the proportion of public school teachers increasing from 68% to 72% and that of private school teachers rising from 74% to 77%. In addition, private school teachers exhibited a stronger inclination to adopt simulation-based approaches, such as compound-mixing demonstrations. Both groups, however, expressed strong agreement regarding the practical significance of STEM education, recognising its role in integrating technology and engineering to connect classroom learning with real-world applications.

Figure 4

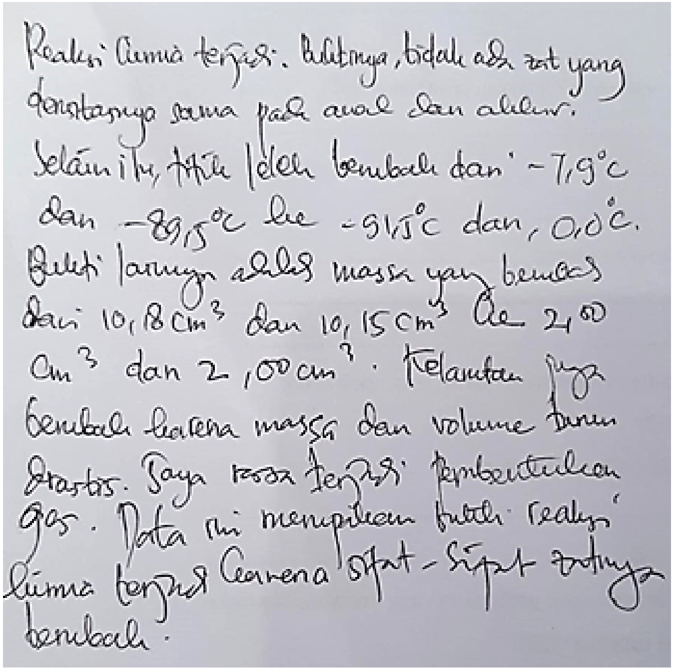
Example answer with the application of CER 1



Ya, terjadi reaksi kimia karena densitas berubah, titik leleh, massa, volume, dan kelarutan besar-besar berubah. Jika tidak ada reaksi kimia, data-data di tabel akan sama.

Figure 5

Example answer with the application of CER 2



Reaksi kimia terjadi. Buktinya, tidak ada zat yang densitasnya sama pada awal dan akhir. Selain itu, titik leleh berubah dari $-7,9°C$ dan $-89,5°C$ ke $-91,5°C$ dan $0,0°C$. Bukti lainnya adalah massa yang berubah dari $10,18 \text{ cm}^3$ dan $10,15 \text{ cm}^3$ ke $2,00 \text{ cm}^3$ dan $2,00 \text{ cm}^3$. Kelarutan juga berubah karena massa dan volume turun drastis. Saya rasa terjadi pembentukan gas. Data ini menunjukkan bukti reaksi kimia terjadi karena sifat-sifat zatnya berubah.

Discussion

Overall, the results of this programme indicate substantial enhancements in teachers pedagogical content knowledge, particularly in integrating three-dimensional learning and scientific inquiry techniques. The pre-post questionnaire results show that both public and private school teachers improved their understanding of STEM principles, but with differing levels of enthusiasm for application. The greater openness of private school teachers to adopting interactive simulations suggests that institutional factors such as resource availability, administrative support, and curricular flexibility influence the adoption of innovative methods, aligning with studies on the importance of school context in STEM reform (Smith et al., 2022; Johnson & Adams, 2021).

The programmes effectiveness in enhancing teachers awareness of STEMs practical relevance is particularly significant. The strong agreement among participants that STEM connects classroom learning to real-world technology and engineering contexts indicates a meaningful shift towards more applied, student-centred pedagogy. This finding supports the theoretical framework of situated learning (Lave & Wenger, 1991), which emphasises knowledge acquisition through authentic and contextually relevant experiences. The observed disparity in enthusiasm between public and private school teachers raises important considerations for future professional development programmes. Although the programme improved conceptual understanding in both groups, the implementation gap suggests that additional support, such as mentoring, resource allocation, or administrative advocacy, may be necessary to ensure equitable adoption of STEM pedagogies across diverse educational contexts. This finding is consistent with research by Johnson and Adams (2021), which highlights the importance of sustained and contextually relevant professional development in bridging the gap between theory and practice in STEM education.

The CER assessment component revealed an important insight, as educators initially struggled to distinguish between superficial data presentation and deeper scientific reasoning when evaluating student work. This finding highlights the need to integrate assessment literacy into STEM teacher training programmes, as the ability to accurately interpret and support scientific argumentation is essential for inquiry-based learning (McNeill & Krajcik, 2011). The results suggest that although short-term intensive programmes can improve teachers STEM knowledge and attitudes, s ustained implementation requires ongoing systemic support. Future efforts should therefore consider differentiated instructional strategies for diverse educational contexts, continuous mentoring and the development of communities of practice, integration into broader school-wide STEM implementation strategies, and policy support for resource allocation and time management.

This study enhances the existing literature on effective STEM teacher professional development by emphasising the opportunities and challenges associated with implementing inquiry-based pedagogies across diverse educational settings. The results underscore that although conceptual comprehension can be attained via specific interventions, altering classroom practices necessitates a more holistic, systemic approach to reforming STEM education.

Conclusion

Summary and Limitations

This community service initiative was carried out as part of a Continuous Professional Development programme focused on STEM Education, to improve the pedagogical content knowledge of science educators. The initiative received financial support from the Institute of Research and Community Service (LPPM) at Universitas Sebelas Maret via the Research Group Grant Programme (PKM HGR UNS). The activities were structured as workshops and training sessions aimed at enhancing educators comprehension and application of STEM -ED methodologies, as well as their proficiency in crafting CER- and modelling-based lessons and evaluating student performance.

Every session wrapped up with a Q&A segment, allowing participating educators to exchange experiences and insights. The programme was effectively implemented, and its success was assessed using evaluation metrics. A comparative analysis of pre- and post-workshop questionnaires indicated notable enhancements in teachers understanding of the materials. The findings revealed distinct outcomes among educators from public and private junior high schools, with those from private institutions exhibiting greater enthusiasm for applying the knowledge and skills acquired from the training sessions.

Implications and the Way Forward

The programme effectively enhanced science teachers pedagogical content knowledge, with participants demonstrating significant improvements in STEM-ED implementation, CER and modelling-based lesson design, and student performance assessment. While these gains were observed among both public and private school teachers, the greater enthusiasm for implementation among private school teachers suggests that contextual factors, such as institutional support, resource availability, and curricular flexibility, may influence the translation of professional development into classroom practice. These findings have important implications for future teacher capacity-building initiatives, emphasising the need for differentiated support mechanisms tailored to specific school contexts. Moving forward, sustainable STEM education reform should incorporate extended mentoring programmes to bridge the gap between theory and practice, school-based professional learning communities to foster peer support, policy interventions that address resource disparities between institutions, and longitudinal studies that examine the impact of contextual factors on STEM pedagogy implementation. This multi-faceted approach will help ensure that professional development programmes not only enhance teachers knowledge but also create supportive environments for transformative STEM education across diverse school settings.

Significance and Contribution in Line with the Philosophy of LSM Journal

This study offers a thorough assessment of a Continuous Professional Development programme focused on STEM Education, emphasising its role in improving science teachers' pedagogical content knowledge through practical training in STEM-ED methodologies, CER techniques, and modelling-based lesson design. This initiative creates a structured workshop framework that effectively connects theoretical training with classroom application and provides a model that can be replicated to enhance teacher capacity in STEM education.

This study makes a significant contribution by empirically demonstrating the effectiveness of targeted programmes in enhancing educators capacity to design and evaluate student -centred STEM lessons. The analysis identifies differences in enthusiasm for implementation between teachers in public and private schools, offering practical insights into how institutional contexts shape professional development outcomes. These findings have important implications for policymakers and educational practitioners, highlighting the need for tailored training approaches that accommodate diverse educational settings, ongoing support structures such as mentoring and professional learning communities to sustain pedagogical content knowledge development, and strategies that promote resource equity to ensure that all teachers can effectively apply their training in practice. By linking teacher development outcomes to broader systemic challenges, this study contributes to the global discourse on equitable STEM education reform and provides a localised framework for the scalable implementation of programmes in Indonesia and comparable contexts.

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