



The Efficacy of STEM-Integrated Teaching Materials in Improving High School Students' Critical Thinking Skills

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Article history	Abstract
Submission : 2025-11-08	Education is a key pillar of a nation's progress. Results from the Program for International Student Assessment (PISA) 2022 indicate that Indonesian students' performance in reading, mathematics, and science remains below international averages, reflecting persistent challenges in higher-order thinking and problem-solving skills. This study aimed to develop STEM-based teaching materials integrated with 21st-century learning to enhance students' critical thinking skills. The research employed a Research and Development (R&D) approach using the 4D model (define, design, develop, disseminate). Participants included material and media experts, chemistry teachers, and 36 Grade XI students. Critical thinking skills were measured using pretest–posttest assessments aligned with Ennis' indicators, expert validation sheets, and student response questionnaires. The results showed that expert feasibility ratings reached 98.05% (highly feasible), user responses were 88.79%, and readability was 87.83%. The effectiveness of the materials was supported by a high N-Gain score of 0.73, indicating substantial improvement in students' critical thinking skills. Overall, the developed teaching materials were feasible, well-received, and effective in improving students' critical thinking skills. These findings imply that systematically integrating STEM principles with 21st-century learning skills can serve as an effective instructional strategy to strengthen higher-order thinking in chemistry education. Future research is recommended to conduct large-scale experimental studies across diverse school contexts and to explore digital integration to enhance scalability and long-term impact.
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1. INTRODUCTION

Education in the 21st century increasingly requires equipping learners with higher-order thinking skills to respond effectively to rapid globalization and technological advancement. Science education, in particular, plays a crucial role in fostering critical thinking, problem-solving, creativity, and decision-making skills that are essential in contemporary society (Drake & Reid, 2020; Herlinawati et al., 2024; Kain et al., 2024). As learning paradigms shift, education is no longer viewed merely as the transmission of knowledge, but as a dynamic process that develops learners' ability to analyze problems, apply concepts, and generate solutions in real-world contexts (Durmuş & Güven, 2025; Perez & Montoya, 2022).

Twenty-first-century learning emphasizes preparing students to respond effectively to the demands of globalization and technological innovation. Learners are expected to master *life skills and higher-order thinking* to succeed in an increasingly dynamic environment (Mulyani et al., 2023). As learning paradigms shift, educational institutions must cultivate critical and creative thinking as core outcomes of instruction (Voogt & Knezek, 2015). These skills are essential for success in contemporary society, where adaptability, innovation, and interdisciplinary understanding are increasingly valued (Boholano, 2017). Thus, integrating 21st-century competencies into classroom practices is imperative to produce learners who are independent, critical, and globally competitive (Sayadi & Pangandaman, 2025).

However, evidence from international assessments indicates that Indonesian students' critical thinking skills in science remain below global benchmarks. The Programme for International Student Assessment (PISA) 2022 reported that Indonesia's performance in science remained below the OECD average, reflecting students' persistent difficulties with analytical reasoning, interpretation of scientific data, and problem-solving (OECD, 2023). Similar findings were reported by Gusman et al. (2023), who identified low levels of analytical and reasoning abilities among students in science learning. These conditions suggest that current science learning practices have not yet optimally supported the development of students' critical thinking skills.

One contributing factor to this issue lies in the characteristics of teaching materials commonly used in classrooms. Existing chemistry teaching materials tend to emphasize theoretical explanations, formula memorization, and isolated concepts, with limited opportunities for inquiry, experimentation, and interdisciplinary connections (Fani et al., 2025; Linda & Arianingrum, 2025). As a result, students often struggle to understand abstract chemistry topics and apply concepts to real-life situations. This challenge is particularly evident in chemical kinetics (reaction rates), which requires students to integrate conceptual understanding, mathematical reasoning, and interpretation of experimental data. Classroom observations at SMA Negeri 12 Semarang further revealed that learning activities were predominantly teacher-centred, with minimal use of interactive worksheets and contextual problem-solving tasks, thereby limiting students' opportunities to develop critical thinking skills.

To address these challenges, an instructional approach that integrates interdisciplinary learning and real-world problem solving is needed. One promising approach is STEM education, which integrates Science, Technology, Engineering, and Mathematics to promote meaningful learning experiences and higher-order thinking skills (Bybee, 2013). STEM-based learning enables students to connect chemistry concepts with technological applications, experimental design, and quantitative reasoning (Istyadji & Sauqina, 2023; Nugraha et al., 2024). Several studies have demonstrated that STEM-based learning is effective in improving students' understanding and critical thinking in specific chemistry topics, such as reaction rates, thermochemistry, and chemical equilibrium, through inquiry-based experiments and problem-oriented tasks (Khalil et al., 2023; Sari et al., 2024; Wu et al., 2022; Zulkifli et al., 2022).

Developing STEM-based chemistry teaching materials is therefore essential to support the implementation of 21st-century learning in chemistry classrooms. Teaching materials serve as pedagogical tools that structure learning activities, facilitate teacher-student interaction, and guide students toward systematic mastery of concepts (Bordoh, 2025). Well-designed STEM-integrated materials can provide inquiry-based learning experiences that actively engage students in analyzing problems, designing experiments, and interpreting data, thereby enhancing critical thinking skills (Dwi et al., 2023; Nurcahyo & Afryaningsih, 2024; Tua et al., 2023; Yasifa et al., 2023).

Previous studies have developed STEM-based chemistry teaching materials in various contexts, such as inquiry-based STEM materials for stoichiometry that were shown to be feasible and effective in improving students' thinking skills (Tua et al., 2023). STEM-based chemistry modules on buffer solution materials that were validated for classroom use (Siregar & Silaban, 2023). Other developments include STEM-oriented student worksheets for atom structure (Zuliatin et al., 2022). While these materials demonstrate the general feasibility of STEM approaches in chemistry learning, most focus on specific sub-topics (e.g., stoichiometry, buffer solutions, atomic structure) and primarily assess overall feasibility or content validity. Few studies have specifically targeted the design of STEM-integrated teaching materials that systematically align STEM components with 21st-century learning skills (4Cs) and explicitly focus on enhancing students' critical thinking indicators in abstract chemical topics such as chemical kinetics. Therefore, a research gap remains in the development of STEM-based chemistry teaching materials that integrate contextual problems, guided inquiry activities, and structured worksheets tailored to both cognitive characteristics and critical thinking enhancement. This study aims to develop such materials to address that gap.

2. METHOD

This study employed a Research and Development (R&D) approach to develop STEM-based chemistry teaching materials integrated with 21st-century learning skills and to examine their effectiveness in enhancing students' critical thinking. The development process followed the Four-D (4D) model proposed by Thiagarajan et al. (1974), consisting of Define, Design, Develop, and Disseminate stages. Rather than emphasising the model's theoretical framework, this study focused on concrete research actions conducted at each stage.



Figure 1. The Four-D Model of Research and Development

Define Stage

The Define stage aimed to identify learning problems and determine the need to develop STEM-based teaching materials. A needs analysis was conducted at SMA Negeri 12 Semarang through classroom observations, interviews with chemistry teachers, and analysis of existing teaching materials. The results indicated that chemistry instruction, particularly on chemical kinetics (reaction rates), relied heavily on textbooks that emphasised theoretical explanations and algorithmic problem-solving. Interactive worksheets, experimental design activities, and interdisciplinary learning experiences were limited. Consequently, students experienced difficulties in interpreting experimental data, analyzing reaction factors, and applying concepts to real-life situations, which directly affected the development of their critical thinking skills. These findings highlighted the need for STEM-based teaching materials that integrate inquiry, experimentation, and real-world problem-solving.

Design Stage

In the Design stage, an initial draft of the teaching materials was developed based on the results of the needs analysis. The product was designed as a STEM-based chemistry teaching module accompanied by student worksheets. The module structure included learning objectives, concept maps, contextual problems, guided inquiry activities, experimental tasks, and critical thinking exercises aligned with 21st-century skills. At this stage, the integration of STEM elements was planned by mapping science concepts (reaction rates), technology applications, simple engineering tasks, and mathematical analysis into each learning activity.

Development Stage

During the Develop stage, the teaching materials were produced and refined based on expert validation. STEM integration in the materials was implemented using the Engineering Design Process (EDP), which includes problem identification, solution planning, experimentation, testing, and evaluation. Students were guided to design simple experiments on reaction rates, analyse data quantitatively, and propose solutions to contextual problems. Product validation was conducted by two validators: one chemistry education lecturer, serving as a subject-matter expert, and one experienced

senior high school chemistry teacher, serving as a practitioner. The validators assessed content validity, presentation, language clarity, graphical design, and STEM integration using a structured validation instrument adapted from established content validation procedures. The validation process followed quantitative content validity analysis as proposed by Aiken (1985), in which expert judgments are converted into coefficient values to determine item relevance and adequacy. The validation data were analysed using percentage-based feasibility criteria, a commonly used approach in educational product development studies to assess validity and practicality.

Disseminate Stage

The Disseminate stage involved a limited classroom trial to evaluate the practicality and effectiveness of the developed teaching materials. The trial was conducted with 35 Grade XI students of SMA Negeri 12 Semarang selected through purposive sampling, as this class represented students who had learned prerequisite chemistry concepts and were suitable for limited-scale product testing in R&D research. Data collection instruments included observation sheets, student response questionnaires, and pretest–posttest critical thinking tests based on Ennis' indicators. Data analysis employed descriptive percentage analyses for feasibility and response data, as well as N-Gain analyses to determine improvements in students' critical thinking skills.

3. RESULTS AND DISCUSSION

This study resulted in the development of STEM-based chemistry teaching materials integrated with 21st-century learning, designed to foster students' critical thinking skills in chemical kinetics for Grade XI students under the *Merdeka Curriculum*. The developed product was prepared in accordance with the Textbook Writing Standards established by the National Education Standards Agency and aimed to address three main objectives: (1) examining the feasibility of the developed teaching materials, (2) evaluating their effectiveness in classroom implementation, and (3) describing students' critical thinking skill profiles after using the materials.

Product Development Results

The development process followed the 4D model, which guided the systematic creation of the teaching materials. Classroom observations and interviews with chemistry teachers were conducted to identify students' learning challenges. The findings revealed that existing teaching references had not yet systematically integrated STEM components. In addition, student worksheets to support inquiry-based and problem-oriented learning were limited. Teachers reported that STEM implementation in chemistry learning tended to be fragmented and superficial, mainly due to limited instructional media and insufficient supporting facilities. These conditions indicated the need for teaching materials that connect chemical concepts with real-world contexts, technological applications, and structured problem-solving activities.

Based on these findings, the teaching materials were designed to align with students' learning needs and curriculum demands. The materials were developed in A4 format (210 × 297 mm) in accordance with BSNP standards, with emphasis on clarity, readability, and visual appeal. The teaching materials consist of several main components, including the cover, preface, table of contents, concept map, user guidelines, learning content, and a closing section. The learning content is organised into three learning activities that integrate STEM elements within chemical kinetics concepts, complemented by student worksheets designed to promote 21st-century skills such as critical thinking, collaboration, creativity, and communication. The complete structure of the developed teaching materials is presented in Table 1.

Table 1. Structure and Pedagogical Function of the Developed Teaching Material

Section	Content Description	Pedagogical Function
Cover	Title, illustration, and material identity	Attract students' attention and introduce the learning context
Preface	Introductory remarks on the material	Provide learning orientation and learning objectives
Table of Contents	List of contents, figures, and tables	Facilitate navigation and independent learning

Section	Content Description	Pedagogical Function
Material Description	Overview of the teaching material	Clarify scope and learning focus
Concept Map	Conceptual framework of chemical kinetics	Support conceptual understanding and knowledge organization
User Guidelines	Instructions for teachers and students	Guide the effective implementation of STEM-based learning
Introduction	Reflection section (<i>Komika Kimia</i>)	Stimulate curiosity through contextual problems
Learning Content	STEM-integrated learning activities and worksheets	Develop critical thinking, collaboration, and problem-solving skills

Feasibility of the Developed Teaching Materials

The instructional design was subsequently developed into a complete product using Canva for visual layout and Microsoft Word for content organization. STEM components, Science, Technology, Engineering, and Mathematics, were integrated across key chemical kinetics topics, including reaction rates, collision theory, factors affecting reaction rates, and rate laws. Furthermore, 21st-century learning skills (4Cs) were embedded through project-based activities, group discussions, contextual problem-solving tasks, and simple experimental activities.

To ensure product quality prior to classroom implementation, a feasibility validation was conducted by three evaluators: two experts in chemistry content and instructional media, and one chemistry teacher as a practitioner. The validation assessed four aspects: content feasibility, presentation, language, and graphical design. The overall feasibility results are summarized in Table 2.

Table 2. Summary of Teaching Material Feasibility Validation

No	Validator	Percentage (%)	Category
1	Validator 1 (Material & Media Expert)	100	Highly Feasible
2	Validator 2 (Material & Media Expert)	95.83	Highly Feasible
3	Practitioner (Chemistry Teacher)	98.33	Highly Feasible
Average		98.05	Highly Feasible

Based on Table 2, the developed teaching materials had an average feasibility score of 98.05%, indicating high feasibility. This high score indicates strong agreement among validators regarding the quality of the developed product. To enhance the credibility of this finding, the validation results were further examined by aspect, as presented in Table 3.

Table 3. Recapitulation of Validation by Feasibility Aspect

Aspect	Percentage (%)	Category
Content Feasibility	97.02	Highly Feasible
Presentation	98.14	Highly Feasible
Language	100	Highly Feasible
Graphical Design	100	Highly Feasible
Average	98.05	Highly Feasible

In addition to quantitative scores, the validators provided qualitative suggestions to refine the teaching materials before final acceptance. These suggestions included clarifying the integration of STEM components within specific learning activities, simplifying technical terminology to improve students' comprehension, and enhancing visual consistency across sections. All recommendations were implemented prior to final validation, indicating that the high feasibility score was achieved through a systematic and iterative revision process rather than a single-stage evaluation.

A more detailed analysis of the content feasibility aspect, which includes material alignment, accuracy, STEM orientation, and integration of 21st-century learning, is presented in Table 4.

Table 4. Validation Results of the Content Feasibility Aspect

Sub Aspect	Percentage (%)	Category
Material Relevance	93.75	Highly Feasible
Content Accuracy	100	Highly Feasible
STEM Orientation	96.67	Highly Feasible
Integration of 21st-Century Learning	100	Highly Feasible

The content feasibility results indicate that the developed materials align well with the learning objectives and students' characteristics related to the chemical kinetics topic. The accuracy sub-aspect received the highest score, suggesting that the presented concepts and examples are scientifically sound and contextually relevant. By linking chemical kinetics concepts to real-life phenomena, the materials support meaningful conceptual understanding, which is essential for the development of higher-order thinking skills. High ratings in STEM orientation and integration of 21st-century learning further indicate that the learning activities successfully embed interdisciplinary thinking, collaboration, and structured problem-solving processes (Davidsson & Enochson, 2016; Giamellaro et al., 2025; Suryawati & Osman, 2018). Overall, the feasibility results confirm that STEM-based chemistry teaching materials integrated with 21st-century learning are highly feasible. The consistently high scores across content, language, presentation, and graphical aspects are closely related to the effective implementation of STEM principles. Real-world problem contexts facilitate students' understanding of abstract chemistry concepts, while engaging visual design and a structured learning flow enhance usability and learning motivation (Habib et al., 2025; Syamala et al., 2025; Webster, 2023). Therefore, the developed materials are considered ready to proceed to the implementation phase through limited classroom trials.

Effectiveness of the Teaching Materials

The effectiveness of the developed teaching materials was evaluated using a pretest–posttest design to assess improvements in students' critical thinking skills, using Ennis's (2011) indicators. The analysis showed a substantial increase in students' performance after learning with the STEM-based chemistry materials. The average N-Gain value was 0.7338 (73.38%), which is categorised as high, as shown in Table 5.

Table 5. Summary of N-Gain Test Results

Average Pretest	Average Posttest	Difference (Post–Pre)	N-Gain (%)	Category
26.94	80.56	53.61	73.38	High

These results indicate that integrating STEM-based learning activities and 21st-century learning strategies positively enhanced students' understanding and analytical abilities. Further analysis based on critical thinking indicators (Figure 2) shows consistent improvement across all measured dimensions.

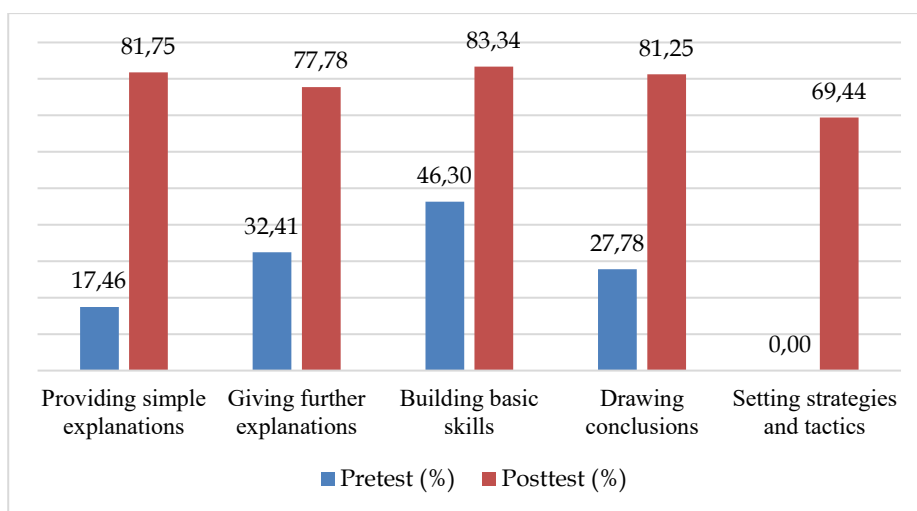


Figure 2. Pretest and Posttest Comparison of Students' Critical Thinking Skills by Indicator

All critical thinking indicators demonstrated significant improvement following the implementation of the developed teaching materials. The highest gains were observed in the indicators of providing simple explanations and drawing conclusions, reflecting students' improved ability to analyze problems, apply scientific reasoning, and formulate evidence-based conclusions. Improvements in the strategy and tactics indicators also suggest that STEM-based learning activities encouraged students to plan, evaluate, and refine problem-solving approaches. These results are consistent with prior research showing that STEM-oriented learning significantly enhances students' critical thinking skills; for example, a quasi-experimental study found that STEM-based learning led to significantly greater improvements in critical thinking outcomes compared with traditional instruction, especially in analysis, evaluation, and problem-solving skills (Busnawir et al., 2024). Furthermore, STEM integration has been shown to increase students' ability to provide logical explanations and draw evidence-based conclusions, with the highest gains often occurring in similar indicators (Lestari & Muhajir, 2021). Systematic reviews of STEM-integrated education also conclude that STEM learning designs positively influence critical thinking competence across contexts by engaging students in authentic problem-solving and inquiry tasks (Azizah et al., 2025).

As a final step, the validated and effective teaching materials were disseminated as an interactive digital book on the AnyFlip platform, enabling easy access for teachers and students. The materials were also shared via email with chemistry teachers and fellow researchers to obtain broader feedback and promote wider implementation (Bektiarso et al., 2023; Hasanah et al., 2025). This dissemination effort supports the advancement of innovative chemistry learning that emphasises STEM integration, conceptual understanding, and the development of students' critical thinking skills, in line with the demands of 21st-century education.

4. CONCLUSION

This study concludes that STEM-based chemistry teaching materials integrated with 21st-century learning are both theoretically valid and practically applicable in the classroom. Developed using the Four-D (4D) model, the materials demonstrated high feasibility across content, presentation, language, and graphical aspects, with an average score of 98.05%, indicating their suitability as instructional resources for senior high school chemistry learning. The effectiveness evaluation showed an improvement in students' critical thinking skills, as reflected in an average N-Gain of 0.7338 (73.38%), categorised as high, suggesting that integrating STEM-oriented activities can support students' analytical and problem-solving abilities in the chemical kinetics topic. From a practical perspective, the materials can be directly implemented by teachers to facilitate contextual, student-centred learning. Future studies are recommended to conduct larger-scale trials in diverse school settings and to integrate the materials into interactive digital platforms or learning management systems to enhance flexibility, collaboration, and adaptability in chemistry instruction.

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