Pancasakti Science Education Journal
PSEJ Volume 10 Nomor 2, Oktober 2025, (Hal. 128 - 135)
http://scienceedujournal.org/index.php/psej
DOI 10.24905/psej.v10i2.286

Submitted:13 Oktober2025, Accepted 29 Oktober 2025, Published:31 Oktober 2025

Validity of 21st-Century Integrated STEM Teaching Materials in Developing Students' Critical Thinking Skills

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Abstrak

Pendidikan merupakan tonggak utama kemajuan bangsa sehingga peningkatan kualitasnya menjadi hal yang krusial. Hasil Programme for International Student Assessment (PISA) 2018 menunjukkan bahwa Indonesia berada pada peringkat ke-73 dari 79 negara dalam kemampuan berpikir kritis, sehingga diperlukan pengembangan bahan ajar yang lebih efektif. Penelitian ini bertujuan mengembangkan bahan ajar kimia berbasis STEM yang layak dan efektif untuk meningkatkan keterampilan berpikir kritis peserta didik. Metode yang digunakan adalah Research and Development (R&D) dengan model 4D (Define, Design, Develop, Disseminate). Data diperoleh melalui observasi, wawancara, angket, tes, dan dokumentasi. Hasil validasi oleh ahli materi, media, dan guru menunjukkan tingkat kelayakan sebesar 98,05% dengan kategori sangat layak. Uji keterbacaan mencapai 87,83%, sedangkan respons peserta didik sebesar 88,79%. Temuan ini menunjukkan bahwa bahan ajar yang dikembangkan memiliki kualitas yang baik dan berpotensi mendukung peningkatan keterampilan berpikir kritis peserta didik.

Keyword: Keterampilan Abad 21; Keterampilan Berpikir Kritis; Pendidikan STEM; Pengembangan Bahan Ajar

Abstract

Education is a fundamental pillar of national progress; therefore, improving its quality is crucial. The 2018 Programme for International Student Assessment (PISA) results reported by the OECD show that Indonesia ranked 73rd out of 79 participating countries in critical thinking skills. This condition highlights the need to develop more effective teaching materials. This study aims to develop STEM-based chemistry teaching materials that are valid and effective for enhancing students' critical thinking skills. The research employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate). Data were collected through observation, interviews, questionnaires, tests, and documentation. Validation by material experts, media experts, and chemistry teachers resulted in a feasibility score of 98.05%, categorized as very valid. The readability test reached 87.83%, while student responses achieved 88.79%. These findings indicate that the developed teaching materials are of high quality and have strong potential to support the improvement of students' critical thinking skills.

Keywords: *21st Century Skills; Critical Thinking Skills; STEM Education. Teaching Materials Development*

INTRODUCTION

Education is a fundamental necessity and a strategic means for addressing future life challenges as an initial step toward sustainability (Tafese & Kopp, 2025). In an era of rapidly advancing globalization, education must be able to adapt to developments in science and technology to remain relevant to current societal demands (Mena-Guacas et al., 2025; Tsekhmister et al., 2024). One of the major challenges in education today is preparing students with 21st-century competencies, which include critical thinking, creativity, communication, and collaboration skills (Nurohmah et al., 2023). Twenty-first-century learning is designed to equip students with essential life skills and the ability to adapt within a highly dynamic global environment (Fitria et al., 2025; Mena-Guacas et al., 2025; Puspa et al., 2023). These competencies are crucial for success in the modern era, as they foster students' development as lifelong learners who are responsive to change (Izhar et al., 2023; Kurniawan et al., 2024).

One of the essential 21st-century skills that must be developed is critical thinking. Critical thinking enables students to analyze, evaluate, and make rational decisions when facing complex problems (Zulyusri et al., 2023). However, various studies have shown that Indonesian students' critical thinking skills remain relatively low. The PISA results released by the OECD (2018) indicate that Indonesia ranked 73rd out of 79 participating countries in the domain of critical thinking. These findings are reinforced by studies conducted by Fitriani et al. (2022) and Haris et al. (2024), which reported that Indonesian students' critical thinking abilities have not yet reached 50% of the expected standard. The low mastery of this skill is influenced by several factors, including the lack of interactive learning media, the use of inappropriate instructional methods, and students' weak higher-order problem-solving abilities (Sastradewi & Agung, 2022; Sinaga & Setiawan, 2022).

To overcome these challenges, teachers must implement innovations in the learning process through the development of interactive and contextual teaching materials. Such materials function not only as a medium of communication between teachers and students but also as an essential tool for facilitating the achievement of learning objectives in a structured and effective manner (Septripiyani et al., 2025; Suarmita et al., 2025). The integration of technology into teaching materials is particularly important, as it aligns with the demands of 21st-century learning, which emphasizes digital literacy, creativity, and learner autonomy. Technology-based teaching materials provide opportunities for students to engage more actively, explore concepts in depth, and construct knowledge through meaningful experiences.

Several studies have also demonstrated that well-designed, technology-supported instructional materials can enhance student motivation, foster higher-order thinking skills, and improve overall learning outcomes (Darmawati & Mustadi, 2023; Miarsyah et al., 2021). Thus, it is essential to implement an instructional approach that not only presents conceptual knowledge but also fosters students' abilities to think critically, innovate, and engage in scientific problem-solving (Guo et al., 2020; Imanah & Handayani, 2023; Khafah & Suprapto, 2023; Subro & Fawaid, 2025).

One of the instructional approaches that aligns strongly with 21st-century learning demands is the STEM (Science, Technology, Engineering, and Mathematics) approach. STEM-based learning integrates four core disciplines to enable students to understand concepts holistically and apply them in real-world contexts (Kelley & Knowles, 2016; Larkin & Lowrie, 2023; Taqwa et al., 2020). This approach not only strengthens students' conceptual understanding but also cultivates critical, creative, collaborative, and communicative abilities skills that are essential for navigating complex challenges and advancing higher-order thinking (Fauzi et al.,

2022; Hayuningrat & Sudarti, 2021; Komalasari et al., 2024; Nikmah & Mandala, 2024).

There is increasing empirical evidence that STEM-based learning is effective in developing students' critical and creative thinking skills, which are essential for 21st-century competencies. For example, a recent meta-analysis found that differentiated STEM learning significantly improves critical thinking across multiple studies (Haetami, 2023) demonstrated through a meta-analysis that STEM-based differentiated learning has a strong positive effect on students' critical thinking. Similarly, Lestari et al. (2024) found that a STEM-PjBL model enhanced students' critical thinking in science learning. Another study by Octafianellis et al. (2021) showed that integrating STEM with problem-based learning improves both critical and creative thinking among secondary-school students. Collectively, these findings underscore that STEM-centered pedagogy supports the development of higher-order thinking, problem-solving, and adaptive reasoning vital skills for learners in our rapidly changing world (Setyobudi et al., 2026).

Based on the foregoing explanation, the development of STEM-based instructional materials offers a promising solution for enhancing students' critical thinking skills. This study aims to develop STEM-based learning materials that are integrated with 21st-century learning principles in order to foster critical thinking skills among secondary school students.

METHOD

In developing the STEM-based instructional materials integrated with 21st-century learning, this study employed a Research and Development (R&D) methodology. The R&D method is used to produce a specific product while simultaneously testing its level of effectiveness (Hanafi, 2017). The research approach adopted in this study follows the 4D development model (Define, Design, Develop, and Disseminate) proposed by Thiagarajan (1974). This model consists of four main stages: the *define* stage, which involves analyzing learners' needs and characteristics; the *design* stage, which focuses on constructing the initial design of the instructional materials; the *develop* stage, which includes producing and validating the product; and the *disseminate* stage, which concerns implementing and distributing the developed materials. Through this study, a STEM-based chemistry instructional material integrated with 21st-century learning principles was produced to train students' critical thinking skills. The stages of the 4D development model are illustrated in Figure 1.

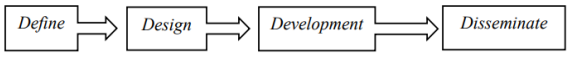

Figure 1. R&D Models by Thiagarajan

The data validation instrument used in this study consisted of questionnaires administered to material experts, media experts, and practitioners. The questionnaires employed a four-point rating scale and assessed several aspects, including content feasibility, presentation, language clarity, and graphical quality. The scores provided by the validators were then converted into percentage values to classify the validity level of the developed instructional materials. The interpretation of these percentages referred to the validity criteria proposed by Akbar (2013), as presented in Table 1.

Table 1. Validity Criteria

Percentage	Criteria
85 - 100	Very Valid
70 – 85	Valid
50 – 70	Fairly Valid
1 - 50	Not Valid

RESULTS AND DISCUSSION

The development model employed in this study is the 4D model, which consists of four

stages: Define, Design, Develop, and Disseminate. This research was conducted up to the development stage in order to evaluate the validity of the resulting product. The first stage, the Define stage, serves as the foundation of the entire development process, as it aims to identify the core learning problems and instructional needs that must be addressed.

At this stage, the researchers carried out classroom observations and conducted interviews to obtain a comprehensive understanding of the challenges experienced by teachers and students. The observations revealed that the learning tools and instructional media used by teachers had not yet been integrated with the STEM approach and were not supported by student worksheets (LKPD). Furthermore, interviews with teachers indicated that STEM-based learning had not been optimally implemented due to limited supporting resources and facilities. These findings provided essential input for determining the direction of product development, ensuring that the instructional materials would align with students' needs as well as the demands of 21st-century learning.

The second stage is the Design stage. At this stage, the researchers drafted the prototype of the STEM-based chemistry instructional materials that would be developed. The design activities included preparing the content draft, determining the structure and sequence of presentation, and creating the layout and visual elements in accordance with the standards set by BNSP. The instructional materials were formatted in A4 size (210 × 297 mm) and designed with visually appealing elements to enhance clarity and increase students' learning motivation. Details of the design process of the instructional materials are presented in Table 2.

Table 2. Instructional Material Design Plan

Page	Content
Cover	Title
	Image
	Instructional material identity
Preface	Preface content
Table of Contents	Table of contents
	List of figures
	List of tables
Description of the Instructional Material	Description of the instructional material
Concept Map	Concept map of the material
Instructions for Using the Instructional Material	For teachers
	For students
Introduction	Reflection (Chemistry Comic/Komika Kimia)
Main Material / Content	Learning Activity 1 (Reaction rate concepts integrated with STEM elements)
	Learning Activity 2 (Collision theory and factors affecting reaction rate integrated with STEM elements)
	Learning Activity 3 (Rate law and reaction order)
	Student Worksheet (Integration of 21st-century learning/21st-century skills)
Closing Section	Competency test
	Glossary
	References
	Postliminary

The development stage continued with a validation process aimed at determining the appropriateness of the STEM-based chemistry teaching material integrated with 21st-century skills. The validation was conducted by material experts and media experts who assessed four main

aspects: content feasibility, presentation, language, and graphical design. The results of this validation are presented in Table 3.

Table 3. Recapitulation of Teaching Material Validation Results

No	Aspect	Percentage
1	Content Feasibility	97.02
2	Presentation	98.14
3	Langauge	100
4	Graphical Design	100
	Average Score	98.05

Based on the results shown in Table 3, the teaching material achieved an average validity score of 98.05%, which falls into the *very valid* category according to Akbar (2013) validity criteria. This indicates that the teaching material is highly suitable for use and only requires minor revisions based on the validators' comments. In terms of content feasibility, the validators stated that the material aligns with the Competency Standards and indicators and is relevant to the STEM approach. Phenomena and learning activities were considered supportive of 21st-century skills, although the validators suggested adding a few more contextual examples and strengthening the connection between the concept map and the sequence of topics presented.

For the presentation aspect, the teaching material was deemed systematic and coherent; however, the validators recommended adding more varied activity designs and additional illustrations related to reaction rate processes. The language aspect received the highest possible score (100%), indicating that terminology, sentence structure, and readability are appropriate for high school students, with no further revision required. The graphical design aspect also achieved a perfect score (100%), reflecting excellent layout, color selection, illustrations, and visual aesthetics. Minor suggestions included adding more white space on certain pages to enhance readability and balance.

Overall, the validation results demonstrate that the STEM-based chemistry teaching material is highly feasible for implementation. Minor revisions suggested by the validators were incorporated before the material proceeded to small-scale and large-scale trials. These results are also consistent with previous studies, such as those conducted by Musyafak et al. (2022) and Rizkika & Ahmad (2022), which reported that STEM-integrated teaching materials consistently obtain high validity ratings and effectively support the development of students' critical thinking skills in problem-based learning contexts.

CONCLUSION

Based on the results of this study, it can be concluded that the STEM-based chemistry teaching materials integrated with 21st-century learning skills were found to be highly feasible for use, obtaining an average feasibility score of 98.05%. These findings indicate that the developed teaching materials meet the criteria for instructional quality in terms of content accuracy, pedagogical suitability, and media presentation.

Furthermore, the teaching materials have the potential to be implemented in school settings as an effective learning resource that supports student engagement, enhances conceptual understanding, and promotes higher-order thinking skills. Future research may focus on evaluating the impact of these materials on student learning outcomes in a broader instructional context.

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