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Development of a Chemistry Teaching Module on Chemical Bonding Based on STEM Integrated with Artificial Intelligence (AI) to Improve Students' Critical Thinking Skills

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Abstract: This research aims to develop a chemistry teaching module on chemical bonding based on the STEM approach integrated with Artificial Intelligence (AI) to improve students' critical thinking skills. The study employs a Research and Development (R&D) method using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The development stages include needs analysis, module design, expert validation, limited trials, and classroom implementation. The module integrates STEM-based learning with AI features such as interactive simulations, adaptive exercises with instant feedback, and chatbot explanations. The validation results show that the module is categorized as valid to very valid with an average score of 3.36–3.80. Limited trials indicate very positive teacher responses and 93.14% of students agreed that the module was effective. Learning outcomes demonstrate that class mastery exceeded 80%, with individual minimum scores above 75. The N-Gain score reached 74.72% in the high category, and the t-test showed a significant difference ($p < 0.05$) between pretest and posttest. These findings conclude that the developed STEM-AI integrated module is valid, practical, and effective for improving students' critical thinking skills in learning chemical bonding.

Keywords: AI; Chemistry; Module; STEM; Technology

Introduction

The Asta Cita, as outlined in the presidential mission, has been incorporated into the National Medium-Term Development Plan (RPJMN) 2025-2029. One of the eight main points in this plan emphasizes the importance of strengthening human resources (HR), science, technology, and education as the foundation for national progress. This vision reflects the government's commitment to building national capacity sustainably through the strengthening of education and research. Parallel to this, the National Research Master Plan (RIRN) for 2017-2045 has already established a framework for national education policy that encourages the integration of technology into learning as part of educational innovation (Ristekdikti, 2017).

Innovative approaches to improving the quality of learning are necessary due to the rapid development of technology and the needs of 21st-century learners. By adapting to these demands, the *Kurikulum Merdeka* has the potential to produce high-quality graduates who are ready to face the future (Lailiyah et al., 2024; Nissa et al., 2025). This curriculum is designed to equip students with fundamental life skills, such as the ability to learn and innovate, use information technology, and think critically in order to actively contribute to society (Manik, 2025; Solehuddin et al., 2024).

However, the *Kurikulum Merdeka*, launched in 2022, faces challenges in the effectiveness of chemistry learning. One of the challenges is that students still struggle to relate abstract chemistry concepts to real-world phenomena (Uthami et al., 2023). Students find

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the complexity of chemistry content difficult to relate to everyday life (Kasman et al., 2022). Additionally, classroom learning often focuses on memorization and mechanical problem-solving rather than on developing critical thinking skills that involve analysis, evaluation, and synthesis of information (Refnita, 2023). Therefore, there is a need for approaches that bring students' everyday experiences into learning, such as the STEM approach (Wijayandaru et al., 2025).

The STEM approach allows students to understand chemical concepts in the context of real-life situations through projects and technology exploration (Ambarwati et al., 2024; Nuraeni et al., 2024). STEM education is deemed essential to prepare the younger generation to face the challenges and demands of the workforce in the Industry 4.0 era and the transition to Industry 5.0, marked by rapid advancements in digital technology (Kasman et al., 2023), the Internet of Things (IoT), big data, and Artificial Intelligence (AI) (Sitopu et al., 2025). Integrating artificial intelligence (AI) provides a solution that can address the demands of current education and the use of appropriate technology in the learning process (Beege et al., 2024; Kasman et al., 2025). AI can help personalize learning, provide interactive simulations (Amrullah et al., 2024), and support data-driven problem-solving (Trinova et al., 2025). This integration can make chemistry learning more interactive, efficient, and relevant to students (Rajwaa et al., 2025; Vedrenne-Gutiérrez et al., 2024).

Typically, STEM approaches and AI-based learning are implemented through learning media used by teachers. One of the most commonly used learning media is the teaching module because it is systematic, structured, and can be used independently by students (Randa et al., 2023). However, existing chemistry teaching modules using the STEM approach, particularly for the topic of chemical bonding, do not yet integrate AI technology (Subandi, 2024).

The STEM approach and AI integration in this teaching module are based on the constructivist theory of Piaget and Vygotsky, where students build knowledge through interaction with the environment and technology (Nugraha et al., 2025; Qomariah et al., 2024). AI integration in STEM-based teaching modules is believed to enhance the instructional impact of chemistry learning, especially in developing students' critical thinking skills (Segal et al., 2025; Subandi, 2024; Yang et al., 2025). AI allows for content personalization, interactive simulations, and automatic evaluations that encourage conceptual understanding and active student engagement (Amrullah et al., 2024). This advantage makes learning more adaptive, efficient, and contextual. However, challenges also arise, such as technology dependence, infrastructure gaps, and the limitations of AI in addressing affective aspects and students' creativity. Therefore, AI integration needs to be carefully designed to maintain pedagogical integrity.

Based on the background, this research aims to answer several questions: First, what are the characteristics of a STEM-based chemistry teaching module integrated with AI that effectively improves students’ critical thinking skills? Second, what is the validity and practicality of the developed STEM-AI integrated chemistry teaching module? Third, how effective is the developed module in improving students’ critical thinking skills in the topic of chemical bonding?

This research addresses issues in chemistry learning within the *Kurikulum Merdeka*, particularly the difficulty students face in understanding the abstract concepts of chemical bonding, the dominance of memorization methods, and the lack of technology integration in learning. The proposed solution is the development of an AI-integrated STEM-based teaching module, enabling students to understand chemical concepts in real contexts through technological exploration. AI will be used to enhance interactivity, such as in chemical bonding simulations, chatbot exercises for concept practice, and an adaptive recommendation system based on students' understanding. With this approach, the learning process is expected to be more contextual, interactive, and supportive of critical thinking development.

The integration of AI in the teaching module will help students visualize abstract chemical bonding concepts, provide adaptive exercises with instant feedback, and support personalized learning. This module is designed to be practical for teachers in implementing technology-based learning. By integrating the STEM and AI approaches, this study aims to make chemistry learning more relevant, efficient, and better prepare students for technology-based work challenges in the Industry 4.0 to 5.0 era.

The primary advantage of the problem-solving approach proposed in this study, compared to previous research, lies in the integration of Artificial Intelligence (AI) within a STEM-based learning module for chemistry education, particularly in the topic of chemical bonding. Previous studies conducted by the researchers (Kasman et al., 2022; Sitopu et al., 2025) and other scholars (Manurung et al., 2023; Wijayandaru et al., 2025) predominantly focused on conventional STEM approaches without incorporating AI technology to enhance learning interactivity and personalization. Moreover, earlier research tended to emphasize the general application of AI in education (Kasman, Suhada, et al., 2024; Kasman & Judijanto, 2024), without developing specific learning media that could be directly implemented in classroom settings.

In terms of novelty, this study presents a STEM-based learning module integrated with Artificial Intelligence (AI), enabling more adaptive and data-driven learning. This approach allows for the use of AI-based interactive simulations, chatbots for concept practice, and personalized learning systems tailored to students' levels of understanding. Thus, this research provides a new contribution to the development of more innovative and technology-oriented chemistry learning (Halawa et al., 2024).

Method

This developmental research employs the Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) (Abuhassna et al., 2024; Lestari et al., 2023). This model was selected due to its systematic structure and suitability for developing instructional modules (Anjasti et al., 2024; Kelana et al., 2024).

The analysis stage of this study focuses on identifying needs and problems in chemistry learning, particularly in the topic of chemical bonding. Activities in this stage include: First, conducting needs analysis through interviews with chemistry teachers. Second, analyzing student characteristics using questionnaires, and third, analyzing instructional materials and learning objectives through a literature review.

Design Stage. Activities conducted at this stage include: First, designing a STEM-based chemical bonding instructional module integrated with AI, aligned with the findings obtained from the analysis stage. Second, Designing research instruments to collect data on the validity, practicality, and effectiveness of the developed instructional module. The instruments consist of: Validity, The validation sheets in this study are divided into two categories: content validation sheets (assessed by media and material experts), effectiveness validation sheets, and practicality validation sheets, which evaluate the implementation of learning as well as teachers' and students' responses regarding the ease of using the module. Practicality, the instruments include observation sheets for learning implementation, teacher response sheets, and student response sheets. Effectiveness, the effectiveness assessment instrument is used to measure students' critical thinking skills before (pretest) and after (posttest) the learning process using the AI-integrated STEM-based module in both control and experimental classes. The assessment instrument is developed based on critical thinking skill indicators (Manurung et al., 2023) and consists of essay-type questions with an allocated completion time of 2 × 45 minutes.

Development stage. The AI-integrated STEM-based instructional module was developed based on the previously designed framework. The development steps are described as follows: First, developing the STEM-based instructional module on chemical bonding, aligned with critical thinking indicators (Draft I). Second, selecting appropriate AI features and embedding several tools into the instructional module. Third, conducting content validation of the module, as well as validation of the effectiveness and practicality instruments, by material and media experts. Fourth, processing the expert validation data and revising the developed instructional module accordingly (Draft II). Fifth, conducting a preliminary trial of the validated module with students of Class XII F2 at SMA Negeri 1 Barru. Sixth, analyzing data obtained from the limited trial. Seventh, refining the instructional module based on the results of the trial data analysis.

Implementation stage. This research was conducted at SMA Negeri 1 Barru during the odd semester of the 2025/2026 academic year. The research subjects were students from classes XI F2 and XI F3. The trial of the validated instructional module was carried out through the following stages: First, conducting the learning process using the AI-integrated STEM-based chemical bonding instructional module. Second, collecting quantitative data through pretests and posttests to measure the improvement of students' critical thinking skills. Third, collecting practicality data from both teachers and students.

Evaluation Stage. Evaluation was conducted to assess the effectiveness of the AI-integrated STEM-based chemical bonding instructional module. The evaluation consisted of the following components: First, formative evaluation at each stage of development. Second, summative evaluation based on students' learning outcomes. Third, revision of the instructional module based on the evaluation results prior to broader implementation (Final Draft).

The data obtained in this study were analysed using both qualitative and quantitative approaches. Qualitative analysis was carried out using thematic analysis techniques based on observational data collected during the implementation stage. Quantitative analysis was conducted by applying descriptive and inferential statistical tests to identify the improvement in students' critical thinking skills through pretest and posttest results. The focus of data analysis in this study includes the validity, practicality, and effectiveness of the instructional module.

The validity analysis was performed by examining the validation data obtained from two experts using Gregory's formula (Anjali et al., 2023). The practicality analysis utilized data from the observation sheets of learning implementation, teacher response questionnaires, and student response questionnaires (Suharyani et al., 2023). The effectiveness analysis was conducted by calculating the n-gain for descriptive testing and applying the t-test for inferential analysis (Anjali et al., 2023).

Result and Discussion

This developmental research employs the Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). This model was selected because it is systematic and well-suited for developing instructional modules.

Analysis Stage, the first stage began with the analysis phase, which aimed to identify needs and challenges in chemistry learning, particularly in the topic of chemical bonding. The activities conducted in this stage included: needs analysis through interviews with chemistry teachers, analysis of student characteristics using questionnaires, and analysis of instructional materials and learning objectives through a literature review.

Based on interviews with two chemistry teachers, several key insights were obtained regarding the needs and problems in teaching chemical bonding. First, the teachers reported that chemical bonding concepts, particularly covalent bonds, metallic bonds, and Lewis structures, are among the most difficult topics for students to understand. These difficulties mainly arise due to the abstract nature of the concepts and students' limited ability to visualize electron movements and molecular shapes (Vonari et al., 2024). As a result, students tend to memorize formulas without fully comprehending the underlying concepts (Barkah et al., 2025).

Commonly used instructional media, such as images, PowerPoint slides, and videos, were perceived as insufficiently effective (Maenah et al., 2024). These media provide only a basic depiction without encouraging students to interact directly with chemical concepts (Zainuddin, 2024). Consequently, students still struggle to relate the material to real-life contexts and often show low engagement in classroom discussions (S. R. Jannah et al., 2025).

Teachers recognized the potential of AI-based technologies to enhance learning. They expressed interest in features such as interactive simulations, practice exercises with instant feedback, chatbots for conceptual explanations, and automated learning analytics. These features are believed to help students grasp abstract concepts more concretely while also fostering critical thinking skills (Kesuma et al., 2025).

While the STEM approach has been considered beneficial, its implementation remains constrained by limited time, resources, and teacher experience in designing relevant projects or experiments. Therefore, the development of a STEM-based instructional module integrated with AI technology is expected to serve as a solution to enhance learning effectiveness, student engagement, and critical thinking skills.

Based on the results of the administered questionnaire, data were obtained regarding students' levels of critical thinking skills in the topic of chemical bonding. From a total of 30 students, the overall score reached 686, with an average of 23.53. The highest score achieved was 27.35, while the lowest was 11.82. The standard deviation of 6.75 indicates a relatively high variation among students' performance. Overall, the average score falls within the low category, suggesting that students' critical thinking skills have not yet developed optimally.

Table 1. Description of Students' Pretest Achievements in Critical Thinking Skills

Variable	Acquisition	Critical Thinking Skill (CTS) Indicators	Percentage (%)	Critical Thinking Skill (CTS) Category
Test Subjects	30	Providing Simple Explanations	25.80	Uncritical
Total Score	686	Building Basic Skills	23.55	Uncritical
Average	23.53	Providing Further Explanations	20.19	Uncritical
Maximum Score	27.35	Managing Strategies and Tactics	30.40	Uncritical
Minimum Score	11.82	Drawing Conclusions	27.95	Uncritical
Standard Deviation	6.75			

The results of the literature review indicate that chemical bonding is one of the fundamental topics in high school chemistry (Ulpa et al., 2025). This topic covers basic concepts related to the formation of bonds between atoms, types of bonds (ionic, covalent, and metallic), Lewis structures, molecular shapes, and the relationship between bond types and compound properties (Nurmayanti, 2024). The nature of this material is abstract, as it requires students to imagine electron movements and visualize molecular structures that cannot be directly observed (Butarbutar et al., 2025).

Difficulties in understanding these abstract concepts often lead students to memorize formulas without fully comprehending the underlying principles (Asrinan et al., 2024). This condition contributes to the low level of critical thinking skills, as students are not accustomed to analysing, evaluating, or connecting chemical bonding concepts to real-life phenomena. Mastery of chemical bonding material should therefore not only aim to enhance conceptual understanding but also serve as a means to develop critical thinking skills. Through a STEM-based learning approach integrated with AI technology, students can interact with simulations, AI-based exercises, and instant feedback. This helps them not only to comprehend abstract concepts more concretely but also to cultivate critical thinking by explaining, analyzing, and evaluating the chemical concepts being studied.

Design Stage, at this stage, a STEM-based chemical bonding instructional module integrated with Artificial Intelligence (AI) was designed based on the results of the needs analysis. The learning objectives were formulated not only to ensure mastery of chemical bonding concepts but also to develop students' critical thinking skills. The critical thinking indicators targeted include the ability to provide simple explanations, build basic skills, offer further explanations, manage strategies, and draw conclusions from observed phenomena (Ningrum et al., 2025).

The module structure was systematically designed, beginning with an introduction containing learning objectives, concept maps, and apperception activities, followed by the presentation of core materials (ionic, covalent, and metallic bonds, Lewis structures, molecular shapes, and compound properties). Each topic is integrated with STEM-based activities involving simple experiments, mini projects, and AI-based simulations. AI technology is incorporated in the form of 3D visualizations, adaptive exercises with automated feedback, and chatbots for conceptual explanations, all of which help students grasp abstract materials more concretely and interactively (Azida et al., 2025).

Additionally, the selected learning media consist of digital modules equipped with illustrations, simulations, and examples of real-life applications. The design of learning activities aims to ensure that students do not merely memorize concepts but are also able to analyze, evaluate, and draw conclusions through contextual learning tasks (Syafawani et al., 2025). The assessment instruments are designed to measure both conceptual understanding and critical thinking skills through problem-based questions, interactive exercises, and simple projects. With this design, the instructional module is expected to serve as a solution to the problems identified during the analysis stage, particularly regarding the abstract nature of chemical bonding and the low level of students' critical thinking skills.

At this stage, research instruments were also designed to collect data on the validity, practicality, and effectiveness of the developed module. The validity instruments in this study consisted of content validation sheets (evaluated by media and material experts), effectiveness validation sheets, and practicality validation sheets, which assess the implementation of learning as well as teacher and student responses concerning the ease of using the module.

The instruments used to measure the practicality of the developed module included learning implementation observation sheets, teacher response questionnaires, and student response questionnaires (Bai et al., 2024). The effectiveness assessment instrument was designed to measure the level of students' critical thinking skills before (pretest) and after (posttest) the learning process using the AI-integrated STEM-based instructional module in both control and experimental classes. The assessment instrument was constructed based on critical thinking skill indicators (Rewara et al., 2024) and consisted of essay-type questions with an allocated time of 2 × 45 minutes.

Development Stage

The STEM-based teaching module integrated with Artificial Intelligence (AI) was developed based on the previously designed framework. This chemical bonding teaching module comprises the module identity, students' readiness—who have already understood the basics of atomic structure but still require a deeper understanding of atomic interactions—material characteristics that include conceptual and procedural knowledge, its relevance to daily life, and graduate profiles that emphasize critical reasoning, creativity, collaboration, independence, and communication skills.

The learning outcomes are focused on students' ability to explain the principles of chemical bonding, draw Lewis structures, predict molecular shapes, and analyze substance properties. The learning objectives are structured across four sessions, covering topics such as atomic stability, ionic and covalent bonding, molecular geometry, and intermolecular forces. These topics are contextualized through real-world phenomena such as the properties of salt, water, diamond, graphite, and metals.

The instructional design is project-based and includes group discussions and digital simulations such as PhET, supported by online platforms like Google Classroom, Google Forms, Kahoot, and Mentimeter. AI integration includes tools such as AI chatbots (e.g., ChatGPT or Claude) for answering questions and facilitating interactive discussions; molecular visualization tools (e.g., MolView or ChemSketch) to draw structures and display 3D models to explain molecular shapes and hybridization; Wolfram Alpha for solving quantitative problems with step-by-step calculations; Canva AI or DALL·E for creating visual illustrations of chemical bonding suitable for posters or summaries; and Labster for virtual lab simulations, providing experimental experiences without a physical laboratory.

The learning steps incorporate mindful, meaningful, and joyful learning, while assessments consist of initial diagnostics, task- and discussion-based formative assessments, and summative assessments in the form of molecular model projects, reports, presentations, and individual reflections.

Validation Results, The content validation results of the developed chemical bonding module show that, overall, the module was deemed valid by subject matter experts and media experts. The aspects of format, content, language, time allocation, and usability were rated as valid to highly valid, with average scores ranging from 3.36 to 3.80. Minor revisions were made, including visual improvements, language refinement, the addition of learning objectives, and adjustments to operational verbs in evaluation questions.

The revision of the effectiveness instrument was carried out based on feedback from validators. In terms of language, revisions included improving word choice to ensure more precise and comprehensible sentences. In the answer key component, revisions included emphasizing expected keywords in bold to clarify the scoring process. Additionally, previously non-detailed indicators for critical thinking were revised to include more explicit descriptions in the assessment blueprint. The initially vague scoring criteria were revised by adding a more detailed rubric, thus enhancing clarity and consistency in the assessment process (Dewi et al., 2023).

Revisions to the practicality instrument aimed to improve clarity, structure, and alignment with the instrument's intended purpose. In the lesson implementation observation sheet, the learning syntax aspects were initially not elaborated in detail, potentially leading to interpretation inconsistencies. Revisions were made to provide clearer descriptions to assist observers in conducting evaluations. In the teacher response questionnaire, there were initially no statements regarding assessment blueprints, instruments, scoring guidelines, or language clarity. Revisions included questions covering these aspects to create a more comprehensive instrument. Similarly, in the student response questionnaire, there were initially no statements regarding language clarity in responding to the module. Revisions included additional statements related to language clarity, enabling more accurate and representative student feedback.

Trial Implementation, following validation, the teaching module underwent a trial phase aimed at refinement prior to full-scale classroom implementation (M. Jannah et al., 2025). The initial trial of the STEM-based teaching module integrated with Artificial Intelligence (AI) was conducted during the odd semester of the 2025/2026 academic year. The trial subjects were 30 students from class XI F 2 at SMA Negeri 1 Barru, representing diverse academic abilities (high, medium, and low). Students were grouped into teams of 5–6 members with heterogeneous composition to ensure balanced group performance.

One of the primary objectives of the limited trial was to evaluate teacher and student responses to the developed module (Chelly Sonelvia Utami et al., 2025). To assess the module's practicality, observations on the implementation of learning activities were conducted, alongside the distribution of teacher and student response questionnaires. The findings from this limited trial were then used to refine the module further and produce the third draft.

Implementation Stage, after undergoing limited trials and revisions, the instructional module draft was further tested to examine its effect on students' critical thinking skills. In this trial, chemistry lessons were conducted over four sessions in classes XI F2 and XI F3, each consisting of 30 students, with the posttest administered in the fourth session.

The practicality of the instructional module can be considered achieved if the learning implementation falls within at least the "partially implemented" category (Syahputra et al., 2024). Based on data analysis, the average score for the implementation of the developed instructional module was categorized as fully implemented, indicating that the module can be effectively used in classroom chemistry instruction, particularly for chemical bonding material. Based on observer assessments and percentage analysis of inter-rater agreement, it can be concluded that the implementation of the chemistry instructional module met the practicality criteria.

Teacher responses to the module were collected through questionnaires designed to evaluate their perceptions of the developed instructional module (Y. Yolanda, 2021). These responses provided insights into the practicality of the learning materials, as the questionnaire included statements about module usability and relevance. The analysis results revealed that the developed module was rated as highly positive, suggesting that the module is practical and feasible for use in classroom chemistry instruction.

Student responses to the learning implementation were also obtained through questionnaires, which yielded an average percentage of 93.14%. This indicates that the majority of students expressed agreement with the STEM-based learning implementation, and all aspects of the instructional process using the developed module received very positive feedback. According to the established criteria, an instructional module is considered effective if student responses are at least in the positive category (Warkintin et al., 2019). Therefore, the results confirm that the developed module is effective for use in learning activities.

The effectiveness of the instructional module was further examined through learning outcome tests, which assessed students' critical thinking skills in the topic of chemical bonding. The posttest data showed satisfactory results, with the class mastery percentage exceeding the minimum mastery criterion (classical mastery) of 80%, and individual students achieving a minimum standard score of 75, as set by SMA Negeri 1 Barru. Furthermore, the N-Gain calculation produced a score of 74.72%, which falls into the high category, indicating a significant improvement. These results demonstrate that the developed instructional module meets the effectiveness criteria (M. Yolanda et al., 2023).

Evaluation Stage

Evaluation was conducted to assess the effectiveness of the instructional module after classroom implementation. The evaluation consisted of two types: formative evaluation and summative evaluation. Formative evaluation was performed throughout each stage of development to ensure the quality of the module in terms of content, design, and AI feature functionality (Taufiq et al., 2024).

Summative evaluation was conducted after the completion of the entire learning process, aiming to determine the impact of the module on students' critical thinking improvement (Purba et al., 2023). The pretest and posttest data were analyzed using N-Gain and t-test analyses. The results showed a significant improvement, with an N-Gain value of 0.64 (categorized as moderate to high) and a t-test significance value of < 0.05, confirming a statistically meaningful increase in students' performance.

Additionally, the questionnaire results indicated that both teachers and students gave positive responses to the module. Teachers stated that the module was easy to use and aligned with instructional needs, while students reported that it helped them better understand difficult concepts and made them more engaged in the learning process (Asmayani et al., 2024).

Based on these evaluation results, a final revision was conducted to refine the module (Fatmawati et al., 2018). The revisions included simplifying instructions, adding illustrations, and enhancing AI features to improve responsiveness. The final draft of the module is therefore ready for broader implementation.

Conclusion

The STEM-based chemical bonding Teaching Module integrated with Artificial Intelligence (AI) developed in this study exhibits systematic and interactive characteristics. The module includes learning objectives, a concept map, core materials, STEM-based activities, and AI-integrated technologies such as 3D simulations, adaptive exercises, and a chatbot. Its interactive digital format, enriched with illustrations, contextual examples, and mini projects, enables the module to encourage students to become more active and skilled in critical thinking. Validation results from material and media experts indicate that the module falls within the valid to highly valid category, with an average score ranging from 3.36 to 3.80. Minor revisions were made concerning language, visual design, and learning objectives. The practicality test revealed that the learning process was fully implemented. Teachers' responses toward the module were highly positive, while students' responses reached 93.14%, indicating that the module is practical and suitable for classroom use. Furthermore, the teaching module proved effective in enhancing students' critical thinking skills. Posttest results showed that the class achieved a learning mastery rate exceeding 80%, with a minimum standard score of 75. The N-Gain score of 74.72% was categorized as high, and the t-test results demonstrated a significant difference between pretest and posttest scores with a significance value of $p < 0.05$. Therefore, this AI-integrated STEM-based teaching module is declared valid, practical, and effective as a learning solution for the topic of chemical bonding in senior high schools.

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Author Contributions

Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, R.A.K., M.F., and M.I. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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