

Development of STEM-AR Interactive Multimedia to Improve Undergraduate Students' Conceptual Understanding of Chemical Bonding

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Received: 25 August 2026

Accepted: 09 October 2026

Published: 20 October 2026

Abstract: Chemical bonding is a highly abstract topic that requires students to connect multiple representations, which may contribute to misconceptions and difficulties in developing conceptual understanding. This study aimed to develop STEM-based interactive multimedia integrated with Augmented Reality (AR) and evaluate its feasibility, practicality, and effectiveness in supporting students' conceptual understanding of chemical bonding. The multimedia was developed using the ADDIE model and involved 35 fourth-semester Chemistry Education students. Feasibility was assessed by subject matter and media experts, while practicality was evaluated by lecturers and students. Effectiveness was measured using a 20-item, three-tier multiple-choice diagnostic test administered as a pretest and posttest. The multimedia was highly feasible based on subject matter (92.01%) and media expert (86.67%) evaluations and highly practical based on lecturer (94.17%) and student (81.48%) evaluations. Conceptual understanding increased from 24.65% to 55.19%, while misconceptions decreased from 42.12% to 27.56% and lack of conceptual understanding from 33.23% to 17.15%. The paired-samples t-test showed a significant difference ($p < 0.001$), with a large effect size (Cohen's $d = 1.74$) and moderate N-gain (0.41). Overall, the multimedia supported improved conceptual understanding of chemical bonding.

Keywords: interactive multimedia, STEM education, augmented reality (AR), conceptual understanding, chemical bonding.

Article's DOI: <https://doi.org/10.23960/jpmipa.v27i4.pp1877-1896>

■ INTRODUCTION

Chemistry is a scientific discipline that requires students to connect multiple levels of chemical representation: macroscopic, submicroscopic, and symbolic. Chemical bonding is one of the fundamental concepts that requires such representational competence, as an understanding of bonding provides the basis for explaining the physical and chemical properties of substances and their interactions (Eikeseth et al., 2026). Nevertheless, chemical bonding remains a challenging concept for students because it involves abstract submicroscopic entities that cannot be directly observed and must

be connected with macroscopic phenomena and symbolic representations (Laohapornchaiphan & Chenprakhon, 2024). In addition to understanding the characteristics of different types of chemical bonds, students are expected to integrate various models of chemical bonding into explanations that are consistent with scientific conceptual frameworks. However, students may employ different models or representations of bonding when explaining chemical phenomena, reflecting variations in the construction of their conceptual understanding (Aakre & Eggen, 2026). In this context, Jeon et al. (2024) demonstrated the potential of augmented reality

(AR) to support the learning of covalent and ionic bonding by providing interactive representations of chemical structures.

Difficulty establishing connections among different levels of chemical representation may lead to misconceptions, which can hinder students' subsequent learning of more advanced chemistry concepts. Identifying misconceptions is an important component of the learning process because undetected conceptual errors may persist over time and influence the development of subsequent knowledge (Peşman & Eryılmaz, 2010). Consistent with this finding, Fahrnis et al. (2025) reported that most undergraduate students remained at the partial understanding level when learning chemical bonding. This finding indicates that students' ability to provide correct answers does not necessarily reflect a complete conceptual understanding. Therefore, learning assessment should provide information not only about the accuracy of students' answers but also about their level of conceptual understanding. Hasdemir et al. (2026) emphasized the importance of reasoning-based assessment instruments for obtaining more in-depth information about students' conceptual understanding.

Conceptual understanding is not only related to the abstract nature of chemical bonding but also to the limitations of instructional media in representing phenomena that cannot be directly observed. Submicroscopic phenomena, such as molecular structures, electron distribution, molecular geometry, and bond formation, require visual representations that can help students construct more concrete mental models. In this context, Augmented Reality (AR) offers an opportunity to present chemical objects through interactive three-dimensional visualizations that students can explore. Jiménez (2019) explained that AR enables the three-dimensional visualization of molecular structures, chemical bonds, and intermolecular interactions, thereby

supporting the development of more accurate mental representations. Furthermore, Zhang et al. (2024) demonstrated that augmented reality and virtual reality technologies can provide immersive and interactive visualization experiences in STEM education, making abstract scientific content more accessible for visualization and exploration.

However, using technology in education does not automatically guarantee improved conceptual understanding. The effectiveness of instructional media also depends on the pedagogical approach underlying its design and learning activities. One relevant approach is Science, Technology, Engineering, and Mathematics (STEM), which enables students to integrate knowledge and practices across disciplines by applying scientific concepts, technology, engineering principles, and mathematical reasoning to address contextual problems (Dalimunthe et al., 2025). Amdayani et al. (2025) demonstrated that STEM-oriented learning can develop students' critical thinking skills and conceptual understanding. Similarly, Deng et al. (2025) showed that an integrated STEM curriculum can connect knowledge and practices across science and technology disciplines to support the development of STEM literacy.

Several studies have examined AR use in chemistry education and demonstrated its potential to support students' understanding of abstract concepts. Rahayu et al. (2025) found that AR-based learning modules can support conceptual understanding of acid-base chemistry through interactive visualizations that connect observable phenomena to molecular-level representations. Similarly, Urun Arici (2026) reported that AR-supported learning enhanced the conceptual understanding of preservice science teachers in learning about intermolecular forces, highlighting the potential of AR to represent chemical interactions that are difficult to observe directly. Furthermore, Bullock et al.

(2026) demonstrated that the effectiveness of AR environments depends not only on the availability of three-dimensional representations but also on how students use, explore, and interpret these representations during the learning process. In addition, systematic reviews of AR and immersive technologies in chemistry education indicate an increasing use of these technologies to represent molecular structures, chemical bonding, and other abstract chemical phenomena (Ribiè & Devetak, 2025; Christopoulos et al., 2026).

Although previous studies have demonstrated AR's potential in chemistry education, research on integrating AR with the STEM approach in interactive multimedia to improve students' conceptual understanding of chemical bonding remains limited. This study integrates STEM into learning activities to encourage students to connect concepts, explore problems, and actively apply their knowledge. At the same time, AR provides three-dimensional visualizations of abstract chemical concepts. Integrating these two components is expected to create a more interactive and meaningful learning experience while supporting students' conceptual understanding of chemical bonding.

Based on the foregoing discussion, this study aims to develop STEM-based interactive multimedia integrated with Augmented Reality (AR) to teach chemical bonding and enhance students' conceptual understanding. The multimedia integrates STEM-based learning activities with AR-assisted three-dimensional visualizations and is evaluated for feasibility by lecturers, practicality based on lecturers' and students' responses, and effectiveness based on changes in conceptual understanding scores from pretest to posttest using a paired-samples t-test, N-gain, and Cohen's d. In addition, the study descriptively analyzes changes in students' conceptual profiles across individual indicators based on the percentages of Conceptual Understanding (CU), Misconception (M), and

Lack of Conceptual Understanding (LCU). Accordingly, this study seeks to determine the feasibility, practicality, and effectiveness of the multimedia in improving students' conceptual understanding and changes in their conceptual profiles across chemical bonding indicators.

■ METHOD

This research adopted a Research and Development (R&D) methodology to develop the proposed instructional product. Product development was guided by the ADDIE instructional design framework, which consists of five sequential stages: Analysis, Design, Development, Implementation, and Evaluation (Molenda, 2003; Stofiana et al., 2026). The model was selected because it provides a systematic framework for designing, developing, implementing, and evaluating instructional products.

Participants

This study included 35 fourth-semester students in the Chemistry Education Program at Universitas Negeri Medan who were enrolled in the Kapita Selektta Kimia course. The students were selected using purposive sampling based on their enrollment in the course and their relevance to the chemical bonding topic examined in this study. In addition to the students, three lecturers who taught the Kapita Selektta Kimia course served as respondents to evaluate the practicality of the developed multimedia.

The study was conducted under research permission issued by the Institute for Research and Community Service (LPPM), Universitas Negeri Medan, through Research Permission Letter No. 0657/UN33.8/LL/2026 and Research Assignment Letter No. 0658/UN33.8/LL/2026, issued on April 10, 2026. Before participating in the study, all students and lecturers were informed of the research purpose and procedures, the voluntary nature of participation,

and the use and confidentiality of research data. Informed consent was obtained from all participants before the study was conducted. Participants' identities were kept confidential by using participant codes during data processing and analysis.

Research Design and Procedures

This study used a Research and Development (R&D) design based on the ADDIE model, which comprises five stages: Analysis, Design, Development, Implementation, and Evaluation. During the Implementation stage, the study examined the multimedia's effectiveness using a one-group pretest-posttest design to measure changes in students' conceptual understanding before and after using the STEM-based interactive multimedia integrated with Augmented Reality (AR). The research was conducted at Universitas Negeri Medan from March to June 2026. The research followed the following stages.

1. Analysis

The Analysis stage involved needs analysis, learning problem analysis, and curriculum and literature review to identify the characteristics of chemical bonding content, students' learning difficulties, and the need for instructional media.

2. Design

The Design stage was conducted based on the analysis results by determining the learning outcomes, content, learning flow, storyboard, navigation structure, interface design, STEM-based activities, and AR components. At this stage, the validation and practicality instruments and the three-tier diagnostic test were also prepared.

3. Development

During the Development stage, the design was transformed into STEM-based interactive multimedia integrated with AR. The initial product

was subsequently validated by subject-matter and media experts to assess the quality of the content, instructional presentation, interface design, and technical and functional aspects of the multimedia. The validation results and expert feedback informed revisions to the product. The revision process continued until the multimedia met the predetermined feasibility criteria for implementation.

4. Implementation

The Implementation stage was conducted to determine the practicality and effectiveness of the developed multimedia. The implementation involved 35 fourth-semester students in the Chemistry Education Study Program at Universitas Negeri Medan who were enrolled in the Kapita Selekt Kimia course. Effectiveness was examined using a one-group pretest-posttest design. Before the learning activities, students completed the three-tier diagnostic test as a pretest. The students then participated in learning activities using the developed multimedia. After completing the learning activities, they completed the posttest using the same diagnostic instrument. In addition, three lecturers teaching the Kapita Selekt Kimia course and the students completed practicality questionnaires to assess the multimedia's ease of use, applicability, and practicality in the learning process.

5. Evaluation

The Evaluation stage was conducted throughout the development process to monitor the multimedia's quality. Formative evaluation was conducted at each stage based on expert validation results and user feedback, which were used to improve the multimedia. Summative evaluation was conducted based on the practicality and effectiveness assessment results to determine whether the developed multimedia met the predetermined criteria for feasibility, practicality, and effectiveness (Mengyao & Ismail, 2025).

Instruments

The instruments used in this study included a subject matter expert validation sheet, a media expert validation sheet, a practicality questionnaire, and a three-tier multiple-choice diagnostic test. The subject matter expert validation sheet was used to assess the feasibility of the content presented in the multimedia, covering the aspects of content feasibility, presentation, and language. The media expert validation sheet assessed design and interface, the use of STEM-integrated AR technology, and independent usability. Both validation instruments were completed by the respective experts to assess the feasibility of the developed product before its implementation.

The practicality questionnaire assessed the multimedia's practicality based on ease of use, interface and AR quality, learning effectiveness, STEM integration, conceptual understanding, and learning motivation and interest. The instrument used to measure students' conceptual understanding was a three-tier multiple-choice diagnostic test adapted from Fahrunis and Sudrajat, (2022). The initial instrument had 25 items and was empirically tested with 36 respondents not included in the study sample. Each item consisted of three tiers: Tier 1, the answer choice; Tier 2, the reason or reasoning underlying the answer; and Tier 3, the level of confidence measured using the Certainty of Response Index (CRI).

Item validity was analyzed using Pearson product-moment correlation. The results showed that 20 of the 25 items were valid, with item total correlation coefficients ranging from 0.377 to 0.693, while five items were considered invalid.

The reliability of the 20 valid items was analyzed using Cronbach's alpha, yielding a coefficient of 0.849, indicating good internal consistency. Therefore, the 20 valid and reliable items were used as the pretest and posttest instruments.

Data Analysis

Data were analyzed using descriptive and inferential statistics to evaluate the feasibility, practicality, and effectiveness of the developed STEM-based interactive multimedia integrated with Augmented Reality (AR).

First, the feasibility and practicality data obtained from the expert validation sheets and practicality questionnaires were analyzed descriptively by expressing the scores as percentages. The percentage score was calculated by comparing the obtained score with the maximum possible score and multiplying the result by 100%. The resulting percentages were interpreted according to the criteria proposed by Sudijono (2005): highly feasible/practical (81-100%), feasible/practical (61-80%), moderately feasible/practical (41-60%), less feasible/practical (21-40%), and not feasible/practical (0-20%).

Second, the effectiveness of the multimedia was examined based on students' responses to the three-tier multiple-choice diagnostic test administered before and after implementation. Students' responses were classified by combining responses from Tier 1 (answer), Tier 2 (reasoning), and Tier 3 (confidence level). The confidence level was measured using the Certainty of Response Index (CRI), with scores ranging from 0 to 5 and classified into high certainty (>2.5) and low certainty (≤ 2.5) (Mellyzar, 2021). The CRI scale is presented in Table 1.

Table 1. Certainty of response index (CRI) scale

Scale	Criterion	Description
0	Totally guessed answer	The answer was completely guessed (100% guessing).
1	Almost guess	Estimated probability of guessing: 75–99%.
2	Not sure	Estimated probability of guessing: 50–74%.
3	Sure	Estimated probability of guessing: 25–49%.
4	Almost certain	Estimated probability of guessing: 1–24%.
5	Certain	The answer was given without guessing (0% guessing).

Based on the combination of responses across the three tiers, students were classified into three categories: Conceptual Understanding (CU), Lack of Conceptual Understanding (LCU),

and Misconception (M). The classification criteria were adapted from Fahrnis et al. (2025). Moreover, are presented in Table 2.

Table 2. Classification of students' response combinations in the three-tier multiple-choice diagnostic test

No.	Response Combination	Tier 1	Tier 2	Tier 3	Category
1	C-C-H	Correct	Correct	High	Conceptual Understanding
2	C-C-L	Correct	Correct	Low	Lack of Conceptual Understanding
3	C-I-L	Correct	Incorrect	Low	Lack of Conceptual Understanding
4	I-C-L	Incorrect	Correct	Low	Lack of Conceptual Understanding
5	I-I-L	Incorrect	Incorrect	Low	Lack of Conceptual Understanding
6	I-C-H	Incorrect	Correct	High	Misconception
7	C-I-H	Correct	Incorrect	High	Misconception
8	I-I-H	Incorrect	Incorrect	High	Misconception

The percentage distribution of students across the three categories was calculated using Equations (1)–(3).

$$\%CU = \frac{CU}{N} \times 100\% \dots (1)$$

$$\%LCU = \frac{LCU}{N} \times 100\% \dots (2)$$

$$\%M = \frac{M}{N} \times 100\% \dots (3)$$

Where:

CU = number of students with conceptual understanding;

LCU = number of students with lack of conceptual understanding;

M = number of students with misconceptions;

N = total number of students.

Third, inferential statistics were used to analyze changes in students' conceptual understanding scores from pretest to posttest. Because the pretest and posttest scores came from the same students, a paired-samples t-test at a significance level of $\alpha = 0.05$ was used to determine whether the two measurements differed significantly. Before conducting the paired-samples t-test, the normality of the paired difference scores (posttest-pretest) was

examined. In addition to statistical significance, the magnitude of the pretest-posttest change was examined using Cohen's d. For paired data, Cohen's d was calculated by dividing the mean of the paired differences by the standard deviation of the paired differences. Reporting the effect size complements the significance test by indicating the magnitude of the observed change rather than only whether the change was statistically significant (Lakens, 2013). Finally, the relative improvement in students' conceptual understanding was analyzed using the normalized gain (N-gain), calculated as follows:

$$N\text{-gain} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}}$$

N-gain was used to describe the magnitude of improvement while taking students' initial scores into account (Hake, 1998).

■ RESULT AND DISCUSSION

Analysis Stage

The analysis results indicated that students still struggled to understand chemical bonding concepts, particularly Lewis structures, hybridization, formal charge, bond calculations,

and molecular shapes and visualization. Interviews with lecturers indicated that the learning media currently used were not optimal for helping students understand structural representations and bond-formation processes. This is linked to the demands of spatial ability and the use of multiple representations in chemistry learning (Rahmawati et al., 2021; Thoms et al., 2026). Atinaf et al. (2026) also reported that undergraduate learning of chemical bonding and molecular geometry requires instructional support that facilitates visualization and conceptual understanding.

The needs analysis also indicated the need for interactive learning media that support the STEM approach and AR technology. This need aligns with the nature of chemical bonding, which involves structures and processes at the submicroscopic level. Digital visualization and immersive technologies can help students understand molecular structures and spatial relationships in chemistry (Badri & Shahat, 2026; Ungu et al., 2025). In addition, analysis of the Kapita Selekt Kimia course syllabus indicated that learning chemical bonding requires students to analyze bond formation, electron structures, substance properties, and intermolecular interactions. Therefore, the analysis of students' needs and characteristics, together with the curriculum requirements, provided the basis for developing STEM-based interactive multimedia integrated with AR.

Design Stage

The design stage was developed based on the results of the needs analysis and focused on developing the blueprint, learning flow, multimedia structure, and research instruments for STEM-based interactive multimedia integrated with Augmented Reality (AR). The multimedia blueprint included learning outcomes, chemical bonding content, STEM-based learning activities, navigation structure, interface design, and integrated learning technologies. The chemical bonding content was organized into three

sections: chemical bonding concepts, orbital-model-based theories, and intermolecular-force-based theories. Each section was designed by integrating Science, Technology, Engineering, and Mathematics through relevant contexts and activities and was complemented by critical thinking activities. These activities included applications of chemical bonding concepts to the Grotthuss mechanism, touchscreen sensors and OLED technologies, shear-thickening fluids, OLED screen engineering, thin-layer chromatography, and calculations involving bond energies and intermolecular forces.

The multimedia flow was designed progressively, beginning with access through Google Sites, followed by content learning, STEM-based activities, molecular visualization using AR, interactive quizzes, competency assessment, and feedback. Google Sites served as the main platform, integrating learning materials, STEM activities through Liveworksheets, 3D molecular visualization through Assemblr EDU, interactive quizzes through Quizizz, and competency assessment through Google Forms. This structure enabled students to access a range of learning resources and activities within an integrated learning environment.

The design was selected because chemical bonding concepts are abstract and require connections among multiple representations. Therefore, AR was integrated as a technological component of the STEM-based multimedia to support students' exploration and reasoning activities progressively. This approach is consistent with research indicating that the use of AR in STEM learning should be accompanied by pedagogical support and scaffolding to enable students to use digital representations meaningfully (Chang, 2026; Hidayat et al., 2026).

Compared with AR-based learning media that primarily emphasize visualization, this design positions AR as part of STEM-based interactive multimedia that integrates molecular visualization with structured learning activities. This approach

aligns with research on AR in chemistry education, which highlights the importance of integrating visualization with learning activities to help students connect different chemical representations (Ribiè & Devetak, 2025; Jeon et al., 2024).

Development Stage

During the Development stage, the design specifications were transformed into interactive multimedia that incorporates the STEM approach and Augmented Reality (AR) for chemical

bonding instruction. Google Sites was used as the main platform for developing the multimedia. The multimedia integrates learning materials, STEM-based student worksheets developed using Liveworksheets, Augmented Reality (AR) based molecular visualizations developed using Assemblr EDU, interactive quizzes using Quizizz, and competency assessments using Google Forms within a single interactive learning environment. The interface of the developed multimedia is illustrated in Figure 1.



(a)

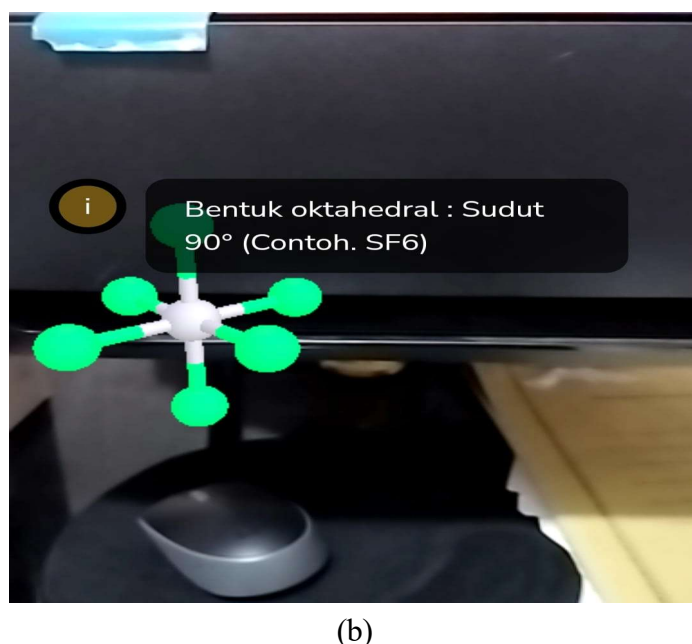


Figure 1. Interface of the STEM-based interactive multimedia integrated with *Augmented Reality* (AR): (a) main interface containing the learning menu; (b) three-dimensional visualization of molecular structures using *Augmented Reality* (AR) technology

Before being implemented, the developed multimedia was reviewed by six experts, comprising three subject-matter experts and three media experts, to establish its feasibility. Evaluation by the subject-matter experts focused on content quality, presentation, and language. Meanwhile, the media experts examined the interface design, the integration of STEM and

Augmented Reality (AR), and the overall usability of the multimedia. The findings from the subject-matter expert assessment are shown in Table 3, and those from the media experts are reported in Table 4.

Based on the findings in Table 3, the subject-matter experts evaluated the developed multimedia and gave it an average score of

Table 3. Results of subject matter expert validation

Aspect	Percentage (%)	Category
Content Feasibility	93.18	Highly Feasible
Presentation	92.86	Highly Feasible
Language	90.00	Highly Feasible

92.01%, classifying it as highly feasible. This score shows that the multimedia content meets

the feasibility standards required for use as a learning medium.

Table 4. Results of media expert validation

Aspect	Percentage (%)	Category
Interface Design	85.00	Highly Feasible
Integration of STEM and Augmented Reality (AR) Technology	85.00	Highly Feasible
Usability	90.00	Highly Feasible

Based on Table 4, the media expert evaluation indicated that the developed multimedia achieved an average percentage score of 86.67% and was classified as highly feasible. This finding demonstrates that the multimedia has satisfactory visual quality and functionality, as well as effective technological integration, making it appropriate for supporting the learning process.

The validation process was followed by product revisions based on feedback from the validators. For the content aspect, revisions were made by correcting chemical notations and representations, including the notation of hybridization, adding material on Lewis structures, correcting typographical errors, and improving the consistency of terminology. For the media aspect, revisions included improving icon consistency, adding instructions for using the multimedia and AR, improving the presentation of the STEM components, and adding quiz feedback to explain correct and incorrect answers. Several unclear images were also improved by searching for better-quality visual sources, although some images were retained because higher-quality sources could not be found. These revisions were intended to improve content accuracy, clarity of presentation, visual consistency, and the usability of the multimedia before the implementation stage.

The development results are consistent with previous studies on technology-based learning media that integrate STEM and AR components. For example, Ramdani et al. (2026) developed a STEM-based inquiry science e-book assisted by AR, demonstrating that AR can be positioned as part of a STEM-based learning environment. In chemistry education, Al Ghawail and Ben Yahia (2026) developed a mobile augmented reality-based learning approach combined with gamification to enhance students' learnability. Meanwhile, Loch et al. (2026) developed an approach to facilitate the creation of three-

dimensional molecular models for AR-based chemistry learning. The development of STEM-based products also emphasizes the importance of validation before implementation (Kamaruldzaman et al., 2026). Compared with these studies, the multimedia developed in the present study integrates STEM, AR, chemical bonding content, critical thinking activities, worksheets, three-dimensional molecular visualization, interactive quizzes, videos, and assessment within a single Google Sites-based multimedia environment.

Implementation Stage

The implementation stage focused on applying STEM-based interactive multimedia integrated with Augmented Reality (AR) to 35 students in the Chemistry Education Program at Universitas Negeri Medan. The multimedia taught chemical bonding through learning materials, STEM-based activities, AR-based molecular visualization, interactive quizzes, and competency assessment. During the learning process, the lecturer served as a facilitator, guiding students to use the multimedia and participate in each learning activity. At this stage, user responses and practicality data were collected through questionnaires administered to three lecturers and 35 students. In addition, the effectiveness of the multimedia was measured using a 20-item three-tier multiple-choice diagnostic test administered as a pretest and posttest.

Based on Figure 2, the three lecturers' assessments showed that the developed multimedia achieved an average of 94.17%, which is categorized as highly practical. This result indicates that, from the lecturers' perspective, the multimedia demonstrated a high level of practicality in supporting the delivery of learning materials, the implementation of learning activities, and the integration of STEM and AR in chemical bonding instruction.

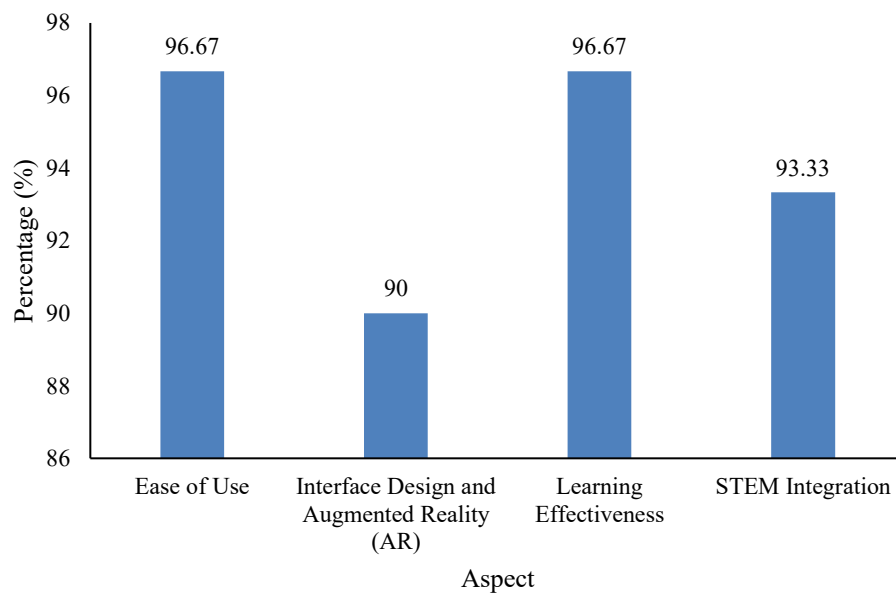


Figure 2. Lecturer practicality assessment results

Based on Figure 3, the assessment of 35 students showed that the developed multimedia achieved an average of 81.48%, categorized as highly practical. This result indicates that students

responded positively to their experience using the multimedia, particularly the interface and AR, conceptual understanding, and learning motivation and engagement.

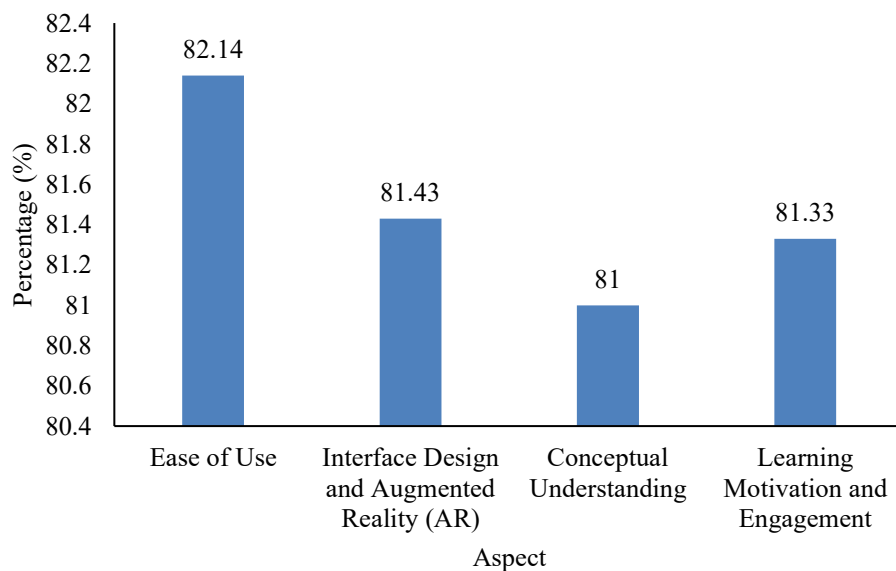


Figure 3. Student practicality assessment results

From a learning process perspective, the multimedia provided an integrated learning environment that combined learning materials, STEM-based activities, AR visualization,

interactive quizzes, and assessment within a single platform. This integration enabled students to follow the learning stages more systematically, beginning with conceptual learning, then exploring

problems through STEM-based activities, observing molecular representations using AR, and checking their understanding through quizzes and assessment. Thus, the multimedia functioned not only as a source of learning materials but also as a learning environment that connected conceptual presentation with exploration activities and opportunities to practice conceptual understanding.

Bottom of FormThe implementation results are consistent with Adewumi et al. (2024), Baeha et al. (2025), Mukaromah and Fibriana (2024), who demonstrated the potential of interactive digital media and AR to support student engagement and learning experiences. Jones et al. (2026) emphasized the importance of usability in the application of AR in chemistry education, while Nguyen Vinh et al. (2026) showed that integrating AR with scaffolding and learning activities can support student engagement. Compared with these approaches, the multimedia developed in this study positioned AR as a technological component for visualizing molecular structures in three dimensions, while learning materials, STEM-based activities, quizzes, and assessments were integrated within a single learning environment. This integration provided more structured support for the learning process, and the evaluation stage further analyzed its effectiveness improving conceptual understanding.

Evaluation Stage

Changes in conceptual understanding across indicators

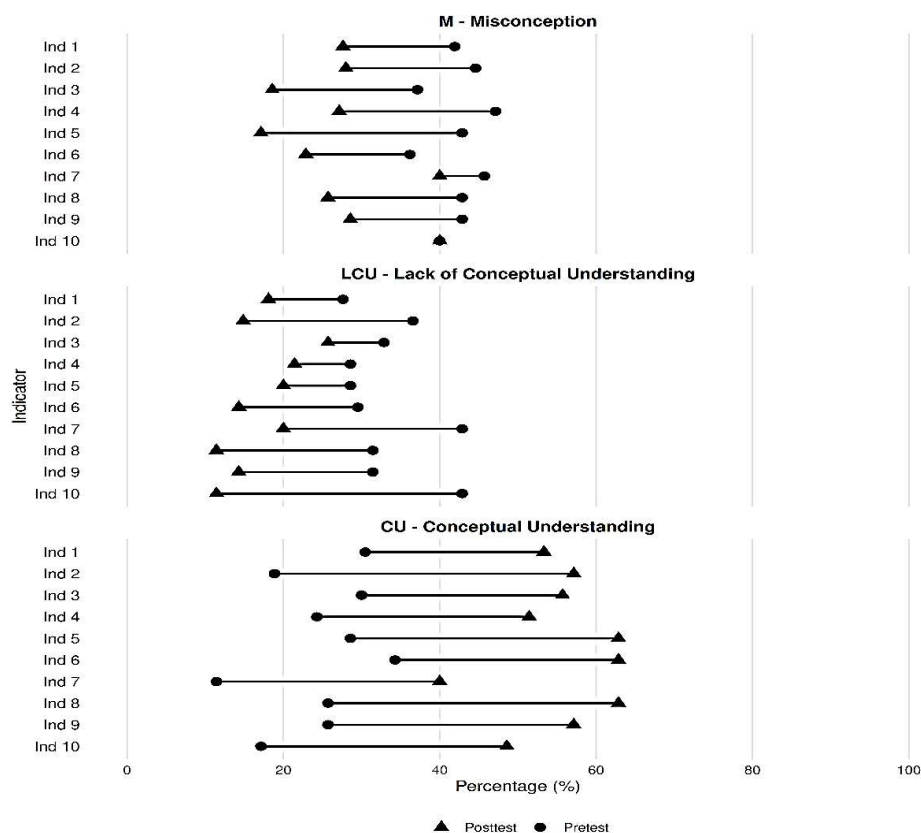
The summative evaluation began by analyzing changes in conceptual understanding categories across the ten chemical bonding indicators. Figure 4 shows the distribution of students across the misconception (M), lack of conceptual understanding (LCU), and conceptual understanding (CU) categories based on pretest and posttest results. Overall, all indicators showed

an increase in the proportion of students classified as having CU after implementing the STEM-based interactive multimedia integrated with Augmented Reality (AR).

The largest increase in conceptual understanding was in the indicator explaining ionic bond formation and the properties of ionic compounds, which rose from 18.86% in the pretest to 57.14% in the posttest. This was followed by explaining intermolecular forces (25.71% to 62.86%) and comparing molecular polarity in compounds (28.57% to 62.86%). Improvements were also observed in explaining the concept and properties of metallic bonds, from 25.71% to 57.14%; explaining the concept and properties of bonding electron pairs (BEPs) and lone electron pairs (LEPs), from 17.14% to 48.57%; and analyzing bond types through Lewis structures, from 34.29% to 62.86%.

Increases were also observed for identifying bond types based on chemical reactions, from 11.43% to 40.00%; analyzing the octet rule in covalent compounds, from 24.29% to 51.43%; explaining covalent bond formation, from 30.00% to 55.71%; and explaining the tendency of atoms to achieve stability based on electron configuration, from 30.48% to 53.33%. Thus, all ten indicators showed an increase in the proportion of students classified as having conceptual understanding.

The increase in the CU category was generally accompanied by decreases in the proportions of students classified as having misconceptions and lacking conceptual understanding. The largest decrease in misconceptions occurred for comparing molecular polarity in compounds, from 42.86% to 17.14%. In contrast, the largest decrease in the lack of conceptual understanding occurred for explaining ionic bond formation and the properties of ionic compounds, from 36.57% to 14.86%. However, the proportion of students



Note: Ind = Indicator

Ind 1 Explain the tendency of atoms to achieve stability based on electron configuration

Ind 2 Explain the process of ionic bond formation and ionic compound properties

Ind 3 Explain the process of covalent bond formation

Ind 4 Analyze the octet rule in covalent compounds

Ind 5 Compare molecular polarity in compounds

Ind 6 Analyze bond types through Lewis structures

Ind 7 Identify bond types based on chemical reactions

Ind 8 Explain the concept of intermolecular forces

Ind 9 Explain the concept and properties of metallic bonds

Ind 10 Explain the concept and properties of bonding electron pairs (BEPs) and lone electron pairs (LEPs)

Figure 4. Distribution of students' conceptual understanding categories across chemical bonding indicators in the pretest and posttest

classified as having misconceptions remained relatively high for identifying bond types based on chemical reactions and explaining the concept and properties of BEPs and LEPs, both at 40.00% in the posttest. This indicates that these two indicators remain relatively challenging for students and require further conceptual reinforcement.

Differences in improvement across indicators indicate that conceptual understanding did not improve equally across all topics. Chemical bonding requires students to connect different representations and concepts at the macroscopic, submicroscopic, and symbolic levels. Difficulties in connecting these representations may contribute to inaccurate

conceptual understanding and misconceptions (Mellyzar, 2021; Fahrnis et al., 2025). The ability to integrate multiple representations of molecular structures is also an important component of chemical reasoning (Bhaskar et al., 2026). Three-dimensional representations can better support understanding of molecular structures and shapes that may be difficult to grasp through two-dimensional representations. Recent research has shown that three-dimensional molecular models based on AR can facilitate the visualization of molecular structures and reduce barriers to the use of AR technology in chemistry learning (Loch et al., 2026). The use of three-dimensional virtual environments can also support chemistry learning at the higher education level, particularly for concepts requiring spatial reasoning and visualization of molecular interactions (Hitlal et al., 2026). Thus, visualization can serve as an additional representation to support students' understanding of abstract chemical concepts; however, it must be embedded in structured learning activities.

For the indicators that continued to show relatively high levels of misconceptions, particularly identifying bond types based on chemical reactions and explaining the concept and properties of BEPs and LEPs, students need to

integrate multiple concepts and engage in more complex reasoning processes. Therefore, visualization alone is insufficient and should be paired with activities that encourage students to interpret, connect, and apply information actively. Approaches that combine visual representations with structured learning activities can support the development of chemical reasoning and conceptual understanding (Sankar, 2026). This is also consistent with the use of interactive learning activities that provide students with opportunities to explore molecular concepts through structured digital learning activities (Maya & Alf  rez, 2026).

Changes in conceptual understanding at the individual level

In addition to changes at the indicator level, the evaluation was conducted at the individual level. Figure 5 shows the relationship between the pretest and posttest conceptual understanding scores of the 35 students. All student data points lie above the diagonal $y = x$ line, indicating that each student scored higher on the posttest than on the pretest. Nevertheless, improvement varied across students. These results indicate that conceptual understanding scores increased for all students, although the extent of change varied.

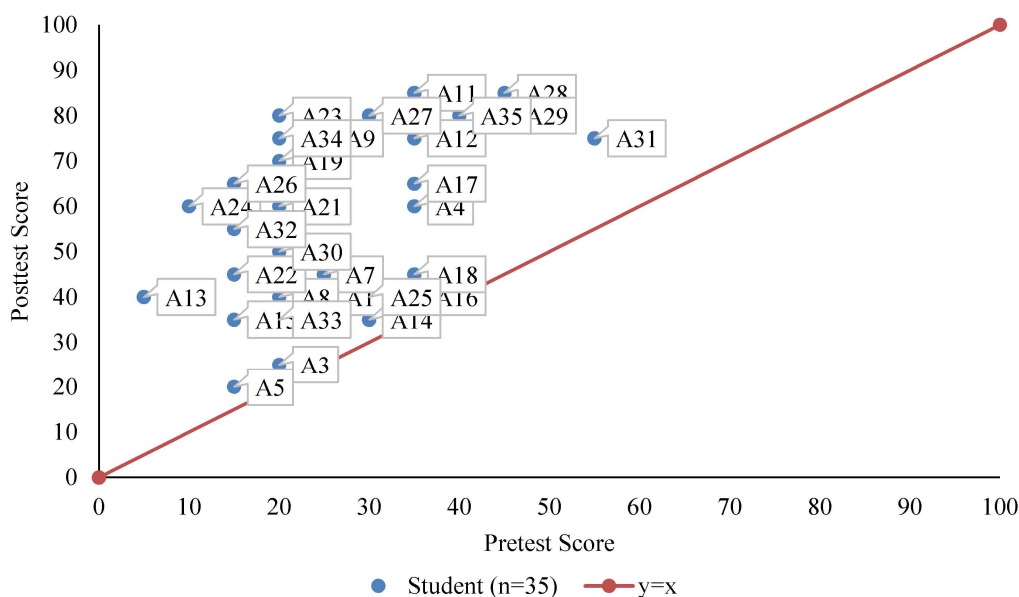


Figure 5. Individual changes in students' conceptual understanding scores from pretest to posttest

The individual-level visualization complements the indicator-level analysis by showing score changes that the category distribution alone cannot reveal. However, the scores presented in Figure 5 represent conceptual understanding scores rather than individual transitions among the M, LCU, and CU categories. This is because both the M and LCU categories received a score of 0, whereas the CU category received a score of 1. Therefore, changes in diagnostic categories at the individual level cannot be determined solely from the points' positions on the graph. The use of diagnostic assessment that considers answers, reasoning, and confidence levels can provide more detailed information about students' conceptual conditions and help distinguish correct understanding from answers obtained through uncertainty or guessing (Eticha et al., 2026 ; Hamerská et al., 2025). Accordingly, interpret the individual scores in Figure 5 as indicators of changes in conceptual understanding. In contrast, changes in the M, LCU, and CU categories are determined by combining responses across the three-tier diagnostic instrument.

The summative evaluation further compared conceptual understanding scores before and after implementing the multimedia. The mean score increased from 26.57 in the pretest to 56.14 in the posttest. The paired-samples t-test indicated a statistically significant difference between the two measurements, $t(34) = -10.321$, $p < .001$.

The magnitude of the change was further analyzed using Cohen's d. The Cohen's d value of 1.74 indicated a large effect size. Reporting the effect size provides information about the magnitude of the observed change, allowing interpretation beyond statistical significance alone (Lakens, 2013; Zieliński & Gawda, 2024). Meanwhile, the N-gain value of 0.41 was categorized as moderate. This value indicates improved conceptual understanding, although the relative gain relative to the maximum possible score remained moderate (Hake, 1998).

These results provide complementary evidence: the category analysis showed an increase in CU and decreases in M and LCU; the individual-level analysis showed that all students experienced an increase in their conceptual understanding scores; and the inferential analysis indicated that the increase in conceptual understanding scores at the group level was statistically significant, with a large effect size. Thus, the evaluation results show not only a change in scores but also the direction, consistency, and magnitude of changes in students' conceptual understanding.

This study employed a one-group pretest-posttest design without a control group; therefore, the observed improvement cannot be attributed exclusively to the multimedia. The variation across indicators and the moderate N-gain (0.41) indicate that AR visualization should be supported by structured reasoning activities and scaffolding (Chang, 2026; Hidayat et al., 2026).

Overall, the multimedia demonstrated feasibility, practicality, and improved conceptual understanding by integrating STEM activities, three-dimensional molecular visualization, interactive quizzes, and a three-tier diagnostic assessment into a single learning environment. AR functioned as a molecular visualization component, while STEM activities supported students' application and reasoning. Thus, the findings provide initial empirical evidence that STEM-based interactive multimedia integrated with AR can support students' conceptual understanding of chemical bonding, rather than definitive evidence of causal effectiveness.

■ CONCLUSION

This study successfully developed STEM-based interactive multimedia integrated with Augmented Reality (AR) for teaching chemical bonding using the ADDIE model. The developed multimedia was rated highly feasible by subject-matter (92.01%) and media expert (86.67%) evaluations and highly practical by lecturer

(94.17%) and student (81.48%) responses. Its implementation was associated with improved students' conceptual understanding: the proportion of students classified as having conceptual understanding increased from 24.65% to 55.19%, while misconceptions decreased from 42.12% to 27.56%. The pretest-posttest difference was statistically significant ($p < 0.001$), with a large effect size (Cohen's $d = 1.74$) and moderate N-gain (0.41). However, the one-group pretest-posttest design without a control group limits causal interpretation. The findings therefore provide initial evidence that integrating STEM-based activities, AR visualization, and interactive assessment within a single learning environment can support students' conceptual understanding of chemical bonding. Further research using controlled or comparative designs is recommended to more rigorously examine the multimedia's effectiveness.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used generative AI and AI-assisted tools, including ChatGPT, exclusively for language-related tasks such as grammar correction, linguistic refinement, clarity improvement, and proofreading. These tools were not used to produce substantive manuscript content, research findings, data, statistical analyses, conclusions, or original intellectual contributions. All AI-assisted content was carefully reviewed, verified, and revised by the authors, who retain full responsibility for the accuracy, originality, and academic integrity of the published work.

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