



Integrating Augmented Reality–Based STEM Comics into Chemical Bonding Instruction to Enhance Students’ Scientific Literacy and Critical Thinking Skills

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ABSTRACT

Purpose: This study examined the integration of Augmented Reality (AR)-based STEM comics into Project-Based Learning (PjBL) for chemical bonding instruction and its relationship with Grade XI students’ scientific literacy and critical thinking skills. **Methods:** A quasi-experimental comparison was conducted at SMA Pergis Maros, Indonesia, involving 40 students: 20 in an experimental group using AR-based STEM comics within PjBL and 20 in a control group using PjBL without AR-based comic media. Essay tests assessed scientific literacy and critical thinking, and data were analyzed descriptively using normalized gain (N-Gain) and inferential statistics. **Findings:** The experimental group’s critical-thinking posttest mean was 75.75, compared with 65.30 in the control group. Mean N-Gain was 0.49 (moderate) in the experimental group and 0.29 (low) in the control group. The reported between-group test was statistically significant ($t = 3.519$, $df = 40$, $p = 0.001$). For scientific literacy, the supplied N-Gain values favored the experimental group across identifying scientific questions (0.76 vs. 0.67), explaining phenomena scientifically (0.85 vs. 0.79), and using scientific evidence (0.94 vs. 0.83). **Implications:** The findings suggest that integrating narrative-based comics, AR visualization, and project-based activities may support scientific literacy and critical thinking in chemistry learning. **Originality:** The study examines the combined use of AR-based STEM comics and PjBL in chemical bonding instruction while considering scientific literacy and critical thinking as distinct outcomes.



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INTRODUCTION

Chemical education plays an important role in developing students’ scientific literacy and critical thinking skills, which are essential for understanding scientific phenomena, evaluating evidence, and making informed decisions. These competencies require students not only to acquire scientific knowledge but also to apply concepts, interpret information, evaluate explanations, and construct evidence-based arguments. The Organisation for Economic Co-operation and Development (OECD) emphasizes that science education should enable learners to explain phenomena scientifically, critically interpret scientific data and evidence, and evaluate scientific information for decision-making and action (OECD, 2025). These competencies are particularly relevant in chemistry, where students are expected to connect abstract theoretical concepts with observable phenomena and practical applications. Consequently, chemistry instruction needs to move beyond memorization-oriented approaches toward learning experiences that actively engage students in scientific inquiry, conceptual reasoning, and problem-solving.

Chemical bonding is a fundamental topic in chemistry because it explains how atoms interact to form molecules and compounds and how these interactions influence the properties of substances. However, understanding chemical bonding can be challenging because the underlying processes occur at the submicroscopic level and cannot be observed directly. Students must relate macroscopic properties, such as the conductivity and solubility of substances, to submicroscopic explanations involving electrons, ions, and molecular structures, as well as to symbolic representations such as chemical formulas and Lewis structures. These demands require learners to coordinate multiple representations

and develop scientifically consistent mental models. Difficulties in understanding chemical bonding and related concepts have been documented in chemistry education research, indicating that students may struggle to connect symbolic representations with particle-level explanations (Tsaparlis et al., 2018). When these conceptual challenges are not adequately addressed, students may have difficulty explaining chemical phenomena, evaluating the validity of scientific claims, and applying chemical knowledge to unfamiliar problems.

One potential approach is the integration of Science, Technology, Engineering, and Mathematics (STEM) principles into chemistry instruction through Project-Based Learning (PjBL). PjBL engages students in investigating meaningful problems, developing project outcomes, applying relevant knowledge, and communicating solutions. When combined with STEM, this approach can provide opportunities for students to integrate scientific concepts with technological applications, engineering design, and mathematical reasoning. In chemical bonding instruction, STEM-oriented projects can situate abstract concepts within contextualized challenges that require students to explain material properties, compare possible solutions, and justify their decisions using scientific principles. Such activities may create opportunities to develop scientific literacy and critical thinking simultaneously. Nevertheless, the success of PjBL depends on the quality of the learning resources, the relevance of the problems presented, and the extent to which project activities require students to engage in evidence-based reasoning rather than merely complete a product.

Augmented Reality (AR) offers an additional opportunity to support the teaching of abstract chemical concepts. By combining digital objects with real-world environments, AR can present three-dimensional visualizations of structures and processes that are otherwise difficult to observe. In chemistry education, such visualizations may help students explore molecular arrangements, examine spatial relationships, and connect symbolic representations with submicroscopic structures. A systematic review by Khairani and Prodjosantoso (2023) examined the application of AR in chemistry learning and identified its potential for presenting chemical concepts through detailed three-dimensional visualizations. Similarly, Mazzuco et al. (2023) reviewed AR applications in chemistry teaching and learning, highlighting the growing role of this technology in chemistry education. However, visualization alone does not guarantee conceptual understanding or the development of higher-order thinking skills (Mei et al., 2026). The instructional design must guide students to interpret the representations, formulate explanations, evaluate evidence, and connect digital models with established chemical principles.

Educational comics provide another complementary resource by combining narrative sequences, illustrations, dialogue, and contextualized problems. These characteristics can help organize scientific information into accessible learning experiences and encourage students to engage with concepts through visual and narrative representations. When designed around STEM principles, comics can present problems that require students to apply scientific knowledge, interpret information, compare alternative solutions, and justify their reasoning. Agussalim et al. (2025), in a systematic literature review of educational comics and AR in chemistry learning, identified the potential of comics to support motivation and initial conceptual understanding, while AR can enrich the representation of abstract chemical concepts. Integrating these media may therefore offer a pedagogically meaningful way to connect conceptual explanations with interactive exploration and project-based activities (Widiastuti et al., 2026). Nevertheless, the combined approach requires empirical evaluation because improvements in motivation or visualization do not automatically translate into measurable gains in scientific literacy and critical thinking.

Scientific literacy and critical thinking are related but distinct learning outcomes. Scientific literacy concerns students' ability to apply scientific knowledge, explain phenomena, interpret evidence, and use scientific information in relevant contexts. The OECD's PISA science framework emphasizes competencies related to explaining phenomena scientifically, constructing and evaluating scientific inquiries, interpreting evidence critically, and using scientific information for decision-making (OECD, 2025). In chemical bonding instruction, these competencies can be assessed through tasks that ask students to explain why substances exhibit particular properties, interpret representations of atomic and molecular interactions, and support conclusions with scientific evidence. Critical thinking, in contrast, emphasizes the quality of students' reasoning, including their abilities to interpret information, analyze relationships, draw inferences, evaluate claims, explain conclusions, and monitor their own thinking. Integrating AR-based STEM comics into PjBL may provide opportunities to develop both outcomes by combining scientific explanation, interactive visualization, evidence-based problem-solving, and reflection.

Despite growing interest in AR and visual learning resources in chemistry education, an important research question remains: to what extent can AR-based STEM comics integrated into PjBL improve scientific literacy and critical thinking simultaneously in the context of chemical bonding instruction? Existing reviews have examined the application of AR in chemistry learning (Khairani & Prodjosantoso, 2023; Mazzuco et al., 2023), while research on chemical bonding has documented persistent conceptual difficulties and the need for instructional approaches that help learners connect different representations of chemical phenomena (Tsaparlis et al., 2018; Widarti et al., 2024). Recent literature has also considered the integration of educational comics and AR in chemistry education (Agussalim et al.,

2025). These studies provide a foundation for the present research, but further classroom-based evidence is needed to evaluate an integrated intervention specifically designed around chemical bonding, STEM-oriented projects, and two complementary learning outcomes. The contribution of the present study is therefore framed not as the first use of AR or comics in chemistry education, but as an empirical examination of their integration within a PjBL-oriented STEM instructional approach.

Accordingly, this study investigates the integration of AR-based STEM comics into chemical bonding instruction at SMA Pergis Maros, Indonesia. It examines differences in students' scientific literacy and critical thinking skills between an experimental group receiving AR-based STEM comics within PjBL and a control group receiving PjBL without AR-based comic media. Scientific literacy is examined through students' abilities to identify scientific questions or issues, explain phenomena scientifically, and use scientific evidence, while critical thinking is assessed using the indicators specified in the study's validated instrument. By examining both learning outcomes, this study seeks to provide empirical evidence on the educational value of combining narrative-based learning resources, interactive visualization, and project-based instruction in secondary chemistry education.

METHOD

Research Design and Participants

This study employed a quasi-experimental design involving an experimental group and a control group to examine the integration of Augmented Reality (AR)-based STEM comics into chemical bonding instruction. The research was conducted at SMA Pergis Maros, Indonesia, involving 40 Grade XI students. The participants were divided into two groups, with 20 students in the experimental group and 20 students in the control group. The experimental group received chemical bonding instruction using AR-based STEM comics integrated with the Project-Based Learning (PjBL) model. The control group received instruction using the PjBL model without AR-based comic media. This comparison was intended to examine differences in students' scientific literacy and critical thinking skills between the two instructional conditions.

Research Instruments

Data were collected using essay tests, observation sheets, and documentation of learning activities. The essay tests were designed to assess students' learning outcomes before and after the instructional intervention. Scientific literacy was assessed using three indicators adapted from the PISA framework: (1) identifying scientific questions or issues, (2) explaining phenomena scientifically, and (3) using scientific evidence. These indicators were used to examine students' ability to identify scientifically investigable questions, apply scientific knowledge to explain phenomena, and interpret evidence to support scientific conclusions.

Critical thinking skills were assessed using indicators covering interpretation, analysis, inference, evaluation, explanation, and self-regulation. These indicators were used to examine students' abilities to interpret information, analyze relationships, draw conclusions, evaluate claims, explain reasoning, and monitor their own thinking. The observation sheet was designed to document students' learning activities using an assessment rubric based on Bloom's Taxonomy. Documentation was used to support the description of the instructional implementation. The research instruments were reviewed by two experts in chemistry education, and reliability was assessed using Cronbach's Alpha. The research instruments were reviewed by two experts in chemistry education, and reliability was assessed using Cronbach's Alpha.

Data Analysis

The data were analyzed using descriptive and inferential statistics. Descriptive statistics included the mean and standard deviation of students' pretest and posttest scores. The Shapiro-Wilk test was used to assess normality, while Levene's test was used to evaluate the homogeneity of variances between the experimental and control groups. Normalized gain (N-Gain) was calculated to describe the improvement in students' scores relative to the maximum possible improvement. Between-group differences were examined using an independent-samples t-test when the relevant assumptions were satisfied. Statistical analyses were conducted using SPSS version 25 for Windows. Scientific literacy and critical thinking were treated as separate outcomes and analyzed independently.

RESULTS

Students' Critical Thinking Skills

The pretest and posttest results were used to examine changes in students' critical thinking skills following chemical bonding instruction. [Table 1](#) presents the descriptive statistics reported for the experimental and control groups.

Table 1. Descriptive Statistics of Critical Thinking Skills

Statistic	Control group	Experimental group
Number of students	20	20
Pretest mean	47.35	50.00
Pretest standard deviation	10.85	10.55
Pretest highest score	64	67
Pretest lowest score	26	33
Posttest mean	65.30	75.75
Posttest standard deviation	13.07	10.12
Posttest highest score	88	88
Posttest lowest score	50	50

Table 1 indicates that the experimental group obtained a pretest mean of 50.00, compared with 47.35 in the control group. Following the instructional intervention, the experimental group achieved a posttest mean of 75.75, whereas the control group achieved a mean of 65.30. The difference between the posttest means was 10.45 points in favor of the experimental group. The experimental group also exhibited a lower posttest standard deviation than the control group, indicating less dispersion in its scores. This descriptive difference alone does not establish that the intervention produced more consistent learning gains for every student.

Normalized Gain of Critical Thinking Skills

Table 2. N-Gain of Critical Thinking Skills

Statistic	Control group	Experimental group
Number of students	20	20
Highest N-Gain	0.53	0.73
Lowest N-Gain	0.18	0.36
Mean N-Gain	0.29	0.49
Category	Low	Moderate

The experimental group achieved a mean N-Gain of 0.49, classified as moderate, whereas the control group achieved a mean N-Gain of 0.29, classified as low. The difference of 0.20 suggests greater relative improvement in the experimental group. N-Gain is a descriptive measure and does not independently demonstrate statistical significance or establish that AR media alone caused the observed difference.

Scientific Literacy

Table 3. N-Gain of Scientific Literacy by Indicator

Scientific literacy indicator	Control group	Experimental group
Identifying scientific questions or issues	0.67	0.76
Explaining phenomena scientifically	0.79	0.85
Using scientific evidence	0.83	0.94

The reported N-Gain values are higher in the experimental group across all three indicators. The largest value in the experimental group was recorded for using scientific evidence (0.94), followed by explaining phenomena scientifically (0.85) and identifying scientific questions or issues (0.76). In the control group, the corresponding values were 0.83, 0.79, and 0.67. These figures suggest a potential advantage for the experimental instructional approach, particularly in the use of scientific evidence.

Inferential Statistical Analysis

Table 4. Reported Inferential Statistics for Critical Thinking Skills

Analysis	Reported result	Interpretation
Shapiro–Wilk normality test	All reported p-values > 0.05	Normality reported as satisfied
Levene's test, pretest	F = 0.032; p = 0.860	Equal variances
Levene's test, posttest	F = 1.251; p = 0.270	Equal variances
Independent-samples comparison	t = 3.519; df = 40; p = 0.001	Significant difference reported

The reported significance value of 0.001 is below the conventional threshold of 0.05, indicating a statistically significant difference between the experimental and control groups in critical thinking skills. The experimental group obtained the higher posttest mean. For scientific literacy, the N-Gain results show higher values in the experimental group across all three indicators.

DISCUSSION

Discussion of Critical Thinking Skills and Scientific Literacy

The findings of this study indicate that integrating augmented reality (AR)-based STEM comics into Project-Based Learning (PjBL) was associated with greater improvements in students' critical thinking skills than PjBL without AR-based comic media. The experimental group achieved a posttest mean score of 75.75, whereas the control group obtained a mean score of 65.30. This difference of 10.45 points suggests that students who participated in the integrated instructional approach demonstrated stronger critical thinking performance after the intervention. The N-Gain results provide further support for this interpretation. The experimental group achieved a mean N-Gain of 0.49, categorized as moderate improvement, while the control group obtained a mean N-Gain of 0.29, categorized as low improvement. Taken together, these findings suggest that the integration of AR-based STEM comics into PjBL may provide additional learning benefits beyond those associated with project-based learning without this media support.

One possible explanation for these findings is the complementary contribution of narrative, interactive visualization, and project-oriented learning activities. STEM comics can present scientific concepts through stories, characters, and contextualized problems that connect abstract knowledge with situations that students can recognize. In chemical bonding instruction, this narrative structure may help students understand why atoms interact, how chemical bonds form, and how bonding relates to the properties of substances ([Rahman et al, 2024](#)). Meanwhile, AR technology can provide interactive visual representations that allow students to explore structures and spatial relationships that are difficult to observe directly. When these features are integrated into PjBL, students can use the representations to investigate problems, develop project outcomes, discuss possible explanations, and communicate scientific conclusions. This combination may encourage students to move beyond memorizing definitions toward analyzing information, evaluating alternative explanations, and constructing conclusions supported by scientific reasoning ([Hidayat et al, 2025](#)).

The potential contribution of this approach is particularly relevant to chemical bonding, a topic that requires students to coordinate macroscopic observations, submicroscopic explanations, and symbolic representations ([Kasman et al, 2026](#)). Students may observe the physical properties of substances at the macroscopic level, but explaining these properties requires an understanding of interactions among atoms, ions, or molecules at the particle level. They must also interpret chemical symbols, formulas, and models to connect these different representations. Difficulties may arise when students can recognize a chemical formula but cannot explain the underlying particle interactions or relate those interactions to observable properties. Interactive AR visualizations may help make these relationships more accessible by providing additional opportunities to examine molecular or particle-level representations. Nevertheless, the educational value of visualization depends on how it is used. Guided questions, discussion, and project tasks are important for encouraging students to interpret representations, explain their meaning, and evaluate the adequacy of the explanations they construct.

The scientific literacy results demonstrate a similar pattern across the three assessed indicators. The experimental group obtained N-Gain values of 0.76 for identifying scientific questions or issues, 0.85 for explaining phenomena scientifically, and 0.94 for using scientific evidence. The corresponding values in the control group were 0.67, 0.79, and 0.83, respectively. Thus, the experimental group recorded higher N-Gain values across all three indicators, with the largest value observed for using scientific evidence. These descriptive results suggest that the integrated instructional approach was associated with improvement in students' capacity to identify scientific issues, explain phenomena, and use evidence in scientific reasoning. The particularly high N-Gain for using scientific evidence may be relevant to the project-oriented nature of the learning activities, which can provide opportunities for students to examine information, connect evidence with explanations, and communicate the basis of their conclusions. However, because the available results are indicator-level N-Gain values, they should not be interpreted as evidence of statistically significant differences between groups unless supported by appropriate inferential analyses.

Scientific literacy and critical thinking are related but distinct learning outcomes. Scientific literacy emphasizes the application of scientific knowledge and practices to understand phenomena and address issues in relevant contexts. Critical thinking, in contrast, focuses on the reasoning processes involved in interpreting information, analyzing arguments, evaluating claims, and drawing justified conclusions ([Brendel et al, 2024](#)). Although these constructs can reinforce one another during chemistry learning, improvement in one does not automatically establish improvement in the other. Therefore, assessing them separately is important for determining the extent to which an instructional

intervention is associated with changes in different dimensions of student learning. In this study, the critical thinking results are supported by posttest scores, N-Gain values, and an independent-samples test, whereas the scientific literacy results presented here are based on comparisons of indicator-level N-Gain values. This distinction should be maintained when interpreting the strength of the evidence for each outcome (Song & Cai, 2024).

Several considerations are necessary when interpreting the findings. First, the experimental condition combined AR-based STEM comics with PjBL, while the control condition used PjBL without AR-based comic media. Consequently, the study evaluates the integrated instructional approach rather than the independent effects of AR technology, comics, or PjBL. Second, the findings are based on the participating students and the specific instructional context; therefore, broader generalizations require further investigation in different schools, student populations, and chemistry topics. Future research could employ larger samples, multiple educational settings, and more differentiated comparison groups to determine which components contribute most strongly to learning outcomes. Additional analyses of scientific literacy, including suitable inferential tests where the underlying data permit, would also strengthen the evidence regarding differences between the experimental and control groups.

Overall, the findings provide evidence supporting the potential of integrating AR-based STEM comics into project-based chemistry instruction to promote critical thinking and scientific literacy. The practical implication is that AR should not be treated merely as a technological enhancement or an attractive visual feature. Instead, it should be embedded in a coherent pedagogical design that connects contextualized narratives, interactive scientific representations, inquiry, and meaningful project activities. By requiring students to interpret models, explain chemical phenomena, examine evidence, and justify their conclusions, teachers can use this integrated approach to create learning experiences that emphasize scientific understanding and reasoning. Further research is warranted to establish the consistency and generalizability of these outcomes and to clarify the specific contributions of the instructional components.

CONCLUSION

The findings indicate that integrating AR-based STEM comics into PjBL for chemical bonding instruction was associated with greater improvement in students' critical thinking skills and scientific literacy than PjBL without AR-based comic media. The experimental group achieved a critical-thinking posttest mean of 75.75 and a mean N-Gain of 0.49, compared with 65.30 and 0.29 in the control group. The reported between-group comparison was statistically significant ($t = 3.519$, $df = 38$, $p = 0.001$). For scientific literacy, the experimental group demonstrated higher N-Gain values across all three indicators. These findings support the use of integrated narrative, AR visualization, and project-based activities in secondary chemistry education.

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AUTHOR CONTRIBUTION STATEMENT

Conceptualization, RAK and MF; methodology, RAK and MF; formal analysis, RAK; investigation, RAK and TLP; data curation, RAK and H; writing—original draft preparation, RAK; writing—review and editing, MF and MFa; visualization, MFa; supervision, MF; project administration, RAK. All authors have read and agreed to the published version of the manuscript.

AI DISCLOSURE STATEMENT

The authors used ChatGPT (OpenAI) during the preparation of this manuscript to assist with language refinement, academic writing, and the organization of the manuscript. After using the tool, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the content of the publication.

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