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Fostering Critical Thinking Skills in Discovery Learning: The Role of a Covalent Bond Simulator

Riani Damay Rosida, *Gun Gun Gumilar, Miarti Khikmatun Nais, Ijang Rohman, Muhamad Nurul Hana

Chemistry Education Study Program, Universitas Pendidikan Indonesia, Bandung, Indonesia.
*Corresponding Author e-mail: gumilarchemi@upi.edu

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Abstract

Critical thinking skills are among the 21st-century competencies that need to be fostered in science education. The abstract nature of the covalent bond concept continues to cause difficulties and misconceptions, potentially hindering the development of critical thinking skills. This study aimed to analyze the role of a feedback-based covalent bond simulator integrated with the Discovery Learning model in fostering students' critical thinking skills. A one-group pre-test post-test design was employed, involving 22 Grade 11 students from a public high school in Bandung. Data were collected using a critical thinking skills test based on Robert Ennis's indicators and analyzed using the Shapiro-Wilk test, Paired Sample t-Test, and Wilcoxon test. The results showed that the mean critical thinking skills score increased from 10.27 to 18.50. Based on the paired-samples t-test, a statistically significant difference was found between the pre-test and post-test scores ($t = -6.475$; $df = 21$; $p < 0.001$), and all critical thinking skill indicators showed significant improvement ($p < 0.05$). These findings provide preliminary evidence that integrating the simulator with Discovery Learning plays a role in facilitating students' critical thinking skills and supporting conceptual understanding for advanced chemistry learning.

Keywords: Critical thinking; Covalent bond simulator; Discovery learning; Feedback-based learning; Conceptual understanding

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INTRODUCTION

In the era of society 5.0, the development of 21st-century skills has become a top priority in education systems across various countries (El-Sayed et al., 2025). The demands of the 21st-century workforce emphasize not only the mastery of technical and academic skills but also cognitive, interpersonal, and digital capabilities essential assets for individuals to adapt and succeed in an ever-evolving environment (Sardar, 2024). The US based Partnership for 21st Century Skills' emphasis on the "4C" concept is communication, collaboration, creativity, and critical thinking highlights the significance of these abilities, which are increasingly acknowledged as crucial intellectual qualities. One essential talent that students need to have in order to handle the difficulties of the twenty-first century is critical reasoning (Fitrianto & Hidayat, 2024). Beyond simply memorizing data, critical thinking entails the capacity to examine issues methodically and reach conclusions based on logic (Solehuddin et al., 2025). As a result, developing critical thinking skills is an important educational goal because these skills are key to students' academic and long-term success.

The five primary components of critical thinking abilities are "elementary clarification, basic support, inference, advanced clarification, and strategy and tactics", according to (Ennis, 2011). Critical thinking involves the ability to evaluate claims objectively, identify reasoning errors, understand logical relationships between statements, and assess the strength of a hypothesis based on evidence and its explanatory power regarding the facts (Ennis, 2011). Critical thinking in science education helps students comprehend difficult ideas, participate in scientific research, and efficiently address issues (Verawati et al., 2024). However, a number of studies show that pupils' critical thinking abilities are still lacking (Shirazi & Heidari, 2019). Indonesian high school students critical thinking abilities are still generally in the low to moderate range (Haris et al., 2024; Jabar et al., 2025; Septiany et al., 2024). Additionally, a teaching strategy that still emphasizes rote memory and one-way knowledge transmission is one of the causes influencing students' poor critical thinking abilities when learning chemistry (Casmini et al., 2024). This suggests that the development of critical thinking abilities in science education is still difficult, especially when it comes to chemistry subjects that call for a high degree of conceptual reasoning proficiency.

Nevertheless, the dense content of science curricula often leads to science being perceived as a highly challenging subject (Wilson et al., 2015). The abstract nature of scientific concepts makes it difficult for students to connect and apply these concepts as well as scientific reasoning to various real-life situations (Tan et al., 2023). In chemistry education, the ability to link macroscopic, submicroscopic, and symbolic representations is a crucial prerequisite for students to develop a deep conceptual understanding (Hasibuan et al., 2026). Chemical bonding is a fundamental topic introduced early in chemistry curricula and serves as a foundation for numerous other chemical topics; however, many secondary school students still struggle to grasp it thoroughly (van Dulmen et al., 2022). Based on their formation mechanisms, chemical bonds are generally categorized into three types: ionic, covalent, and metallic bonds (Brown et al., 2012). The concept of chemical bonding plays a vital role in understanding the relationship between a compound's structure and its properties, and it serves as a basis for studying other chemical concepts, such as thermodynamics (Hunter et al., 2022).

Among the subtopics of chemical bonding, covalent bonding is frequently perceived as difficult by students because it requires an understanding of electron configurations, valence electrons, the octet rule, and Lewis structure representations. This difficulty is compounded by the fact that these concepts cannot be directly observed and require the ability to link submicroscopic representations with symbolic ones. Research by (Khoirunnisa & Sabekti, 2020) indicates that students' average critical thinking skills regarding chemical bonding remain at a low level. Consistent with these findings, a study by (Rohmah et al., 2022) shows that students continue to struggle with chemical bonding specifically covalent bonding as evidenced by the fact that 53% of students harbor misconceptions about the topic. Reveals that students still hold misconceptions regarding covalent bonding particularly in determining bond types, drawing Lewis structures, and explaining bond formation processes stemming from a poor understanding of Lewis structures and the role of electrons in covalent bond formation (Istiqomah et al., 2021). Furthermore, students were found to harbor misconceptions regarding molecular polarity, especially concerning the relationship between electronegativity differences and a molecule's polarity (Prodjosantoso et al., 2019). Therefore, there is a need for instructional media that can help students visualize the process of chemical bond formation in a more concrete way.

Numerous studies show that using digital learning resources can enhance students' understanding of chemical bonds (Widarti et al., 2024). Integrating interactive digital media can provide a learning experience that is more meaningful and responsive to students' needs, thereby fostering engagement, creativity, and critical thinking skills while minimizing misconceptions (Anggitarachmawati, 2025). While Articulate Storyline interactive media has been shown to produce higher learning results than traditional media (Sundari & Pasar Maulim Silitonga, 2022), Google Sites-based media has been shown to be useful in improving students' multi-representation abilities (Danin & Kamaludin, 2023). Additionally, the incorporation of Javalab simulation media into instruction shows a positive impact on the comprehension of chemical bonding concepts (Simanjuntak et al., 2026), and video-based learning materials based on contextual learning are known to enhance students' critical thinking abilities (Latifa et al., 2023). Furthermore, research by (Syawal et al., 2022) demonstrates that using the ChemDraw simulator in lessons on covalent bonding can boost students' conceptual understanding to 95.2%. These results suggest that students may be better able to comprehend the idea of chemical bonding with the use of digital learning resources. As a result, there is a need for media that, for example, use learning simulators to enable students to interactively investigate the process of chemical bond formation in addition to providing information. Therefore, learning simulations that help students grasp chemical bonding ideas and foster the growth of critical thinking abilities are therefore necessary.

One instructional tool that can be used to visualize the concept of covalent bonds is a simulator focused on chemical bonding. Beyond the use of appropriate instructional media, selecting a suitable learning model is also a crucial factor in enhancing student motivation, active engagement, and learning outcomes (Suwandi et al., 2024). One learning model capable of fostering the development of these skills is Discovery Learning. The Discovery Learning model contributes significantly to developing students' critical thinking skills by providing opportunities for them to discover and construct knowledge independently through processes of inquiry and discovery (Pratiwi et al., 2025). According to research by (Simanjuntak et al., 2026), using simulation media in conjunction with Discovery Learning has the potential to produce a more meaningful learning experience, especially when it comes to abstract chemistry ideas. Additionally, students' Higher Order Thinking Skills (HOTS) in the study of chemical bonding are improved when the Discovery Learning paradigm is applied with the help of digital media (Laia & Jahro, 2026). Consequently, implementing a covalent bond simulator integrated with the Discovery Learning model has the potential to help students understand the concept of covalent bonds while simultaneously developing their critical thinking skills.

Research incorporating simulators into the covalent bonding sub-topic to enhance critical thinking skills based on Ennis's indicators remains restricted, despite the widespread use of learning media and the Discovery Learning approach in chemistry education. These critical thinking abilities include the capacity for analysis, evaluation, and logical conclusion-drawing (Andrianto & Qodr, 2025). By including a simulator into the covalent bonding sub-topic of a Discovery Learning model, this study presents an innovative method. It is meant to function as a substitute digital media-based chemistry teaching approach that develops students' critical thinking abilities. Thus, using the Discovery Learning approach, the study intends to examine how an interactive simulator which not only makes concept visualization easier but also offers instant user feedback supports students' critical thinking abilities with relation to covalent bonding. Therefore, the combination of simulation-based media and the Discovery Learning model is expected to create an effective learning environment that fosters the development of students' critical thinking skills.

METHOD

Research Design

This study employs a quantitative approach that focuses on the collection and analysis of numerical data (Creswell, 2014). Specifically, it uses the pre-experimental design with one-group pretest-posttest (Jimenez-Buedo, 2018). In this strategy, a single group of participants is observed both before and after an intervention or treatment is administered (Jimenez-Buedo, 2018). This design is used to assess improvements in students' critical thinking skills following instruction on covalent bonding that utilized a simulator implemented through the Discovery Learning model. Participants are assessed both before and after the intervention using pre-test and post-test measures. Changes in participants' performance between the two assessments are used to evaluate the effectiveness of the intervention (Capili & Anastasi, 2024). The research design is described as follows:

Table 1. Research design

Group	Pre-Test	Treatment	Post-Test
Experiment	O_1	X	O_2

Research Participants

The study was conducted with Grade XI students at a public high school in Bandung during the even semester of the 2025/2026 academic year, these students had previously studied the topic of covalent bonding during the first semester. Consequently, they possessed prior knowledge regarding covalent bonding concepts such as valence electrons, Lewis structures, the formation process of covalent bonds, and polarity. Participants were selected using a convenience sampling technique, taking into account the relevance of the covalent bonding material taught at that grade level. A total of 22 students participated in the study, taking part in both the instructional activities and the data collection process.

Research Instrument

A critical thinking skills test comprising both a pre-test and a post-test serves as the primary instrument in this study. The critical thinking test was developed in accordance with Robert Ennis's critical thinking framework, encompassing the indicators of elementary clarification, basic support, inference, advanced clarification, and strategy and tactics. The test's open-ended questions on the subtopic of covalent bonding are intended to gauge students' aptitude for problem analysis, evidence-based reasoning, conclusion drawing, explanation, and problem-solving techniques. There are 7 questions on the test, and the maximum score is 30. An illustration of a question for the "focusing attention on a question" critical thinking skill indication is "The elements Carbon (C), Nitrogen (N), Oxygen (O), and Neon (Ne) are known to have the atomic numbers C = 6, N = 7, O = 8, and Ne = 10, respectively".

Prior to usage, two Chemistry Education lecturers and one high school chemistry teacher verified the instrument using the expert judgment approach. This strategy was used to guarantee that the instrument items accurately represented the desired constructs, hence increasing the instrument's construct validity (Lim, 2024).The validation method included evaluating the alignment of critical thinking skill indicators, the applicability of the material, the architecture of the items, and the clarity of language The validation results stated that the instrument was "suitable for use with revisions". After that, the instrument was changed in response to the validators' ideas and feedback before being employed in the study.

An analytical rubric created utilizing Ennis's critical thinking skill indicators was used to score student responses. Focusing on a question (0-4), analyzing arguments (0-3), posing and responding to clarification and challenge questions (0-4), choosing an action (0-5), inducing and assessing induction results (0-5), evaluating source credibility (0-5), and definition strategies (0-4) are all indicators that use a scoring scale that is specific to the complexity of the competency being measured. To guarantee consistency and objectivity in the scoring process, the grading rubric included conceptual accuracy, the completeness of arguments, the use of scientific evidence, and the soundness of reasoning.

The Student Worksheet serves as a guide for student activities during lessons utilizing the Discovery Learning model. It is designed to align with the stages of the learning process and incorporates activities such as stimulation, problem formulation, data collection, data processing, verification, and generalization or conclusion formulation.

Reflection sheets are used to gather information regarding students' learning experiences during the lesson, as well as their feedback on the use of the covalent bond simulator application. The information obtained from these sheets serves to provide an overview of student responses to the learning process that has taken place.

Data Analysis Techniques

Pre-test and post-test data were analyzed to determine changes in students' critical thinking abilities. Data normality was assessed using the Shapiro-Wilk test to determine the appropriate statistical analysis. The paired-sample t-test is used to analyze data with a normal distribution, whereas the Wilcoxon signed-rank test is used for data with a non-normal distribution (Isbell & Jiang, 2025). In the paired-samples t-test, effect size was calculated using Cohen's d. Additionally, data from student worksheets and reflection sheets were analyzed descriptively to support the interpretation of the research findings.

RESULTS AND DISCUSSION

Results

This study was carried out with 22 Grade XI students (second semester) who had previously studied covalent bonding during the first semester. As a result, the students were already familiar with concepts such as valence electrons, Lewis structures, and the covalent bond formation process. This suggests that the study's instruction did not intend to introduce covalent bonding concepts for the first time; rather, it sought to improve students' critical thinking skills by including a simulation application into the Discovery Learning approach. Participants participated in the whole study process, beginning with the pre-test and instruction using the covalent bonding simulation application (using the Discovery Learning paradigm) and ending with the post-test and completion of learning reflection sheets.

The covalent bond simulator is an Android-based application designed to assist students in visualizing abstract concepts related to the covalent bonding sub-topic. Figure 1 highlights the simulator's primary features. Before beginning the simulation, students are given an introduction and usage instructions, which include animations of electron placement and a demonstration of the drag-and-drop feature. During the simulation, students can use a variety of tools, including a periodic chart with atomic numbers, electron configurations, and electronegativity values, as well as functions to add electrons and single, double, or triple covalent bonds to their workspace. Figure 2 shows an example of a Lewis structure created by a student with the covalent bonding simulator. An answer-checking function also provides rapid feedback on the accuracy of the Lewis structures that have been developed.

Figure 1. Lewis Structure Construction Simulation Framework

Figure 2. Result of constructing the Lewis structure on the framework

The simulator includes a variety of assistance features such as usage instructions, learning resources, level selection, and a periodic table of elements with atomic numbers, electron configurations, and electronegativity values. The application also has an answer-checking feature (feedback) that allows students to immediately examine the accuracy of their responses, as well as a results-saving system for reviewing work performed at each level, as illustrated in Figure 3.

Figure 3. Level selection frame

From an introduction to valence electrons and Lewis structures to an examination of molecular polarity, the simulator's content is arranged into six stages that are presented one after the other. To ensure a methodical learning process that corresponds with the material's growing complexity, students must finish each level in order before moving on to the next. With the help of this structure, students can gradually investigate ideas, check their work with feedback from the application, and edit their responses if mistakes are discovered. Therefore, before analyzing the implementation outcomes based on shifts in students' critical thinking abilities, the simulator supports processes of exploration, evaluation, and reflection consistent with the Discovery Learning approach in addition to acting as a visualization tool for covalent bonding concepts.

The training was divided into two sessions of five instructional periods, each lasting 45 minutes. Throughout the learning process, the teacher served as a facilitator, guiding students, moderating discussions, and aiding them in using the simulation program in accordance with the Discovery Learning stages. Meanwhile, the students participated actively by studying the notion of covalent bonds using the simulator, performing tasks on the student worksheet, and expressing their results throughout the learning process.

The first step in implementing Discovery Learning is the stimulation phase, which involves presenting a contextual phenomenon related to oxygen molecules (O_2) and the human respiratory process. Students are instructed to identify the issue and relate it to their past understanding of valence electrons and covalent bond formation using guided questions; this step mainly supports the signal of "focusing attention on a question." Students then create questions on Lewis structures, atomic stability, and the process of covalent bond formation during the problem statement phase activities that promote the capacity to "ask and answer clarifying questions". During the data collecting stage, students utilize a simulation application to investigate electron configurations, valence electrons, and the building of Lewis structures, then write their findings on the worksheet. This practice develops the capacity to "analyze arguments and assess the credibility of a source" using information gained from the simulator. During the data processing stage, students evaluate their findings to establish the proper Lewis structure and the reasoning behind it, and then verify their answers with the application's feedback feature during the verification stage. Students can "determine a course of action" and "induce and evaluate the results of induction" depending on the evidence gathered via this procedure. Students draw conclusions about the connections between Lewis structures, covalent bond formation, and molecular properties during the lesson's generalization phase. Through the methodical development of concepts based on the findings of the investigation, this activity supports the "defining strategy" indicator.

Following the implementation of instruction using a covalent bond simulator based on the Discovery Learning model, students took a post-test designed around Ennis's critical thinking skill indicators. To give a preliminary picture of how students' critical thinking abilities changed before and after the teaching, pre-test and post-test data were first descriptively examined. A comparison of the overall mean scores and the scores for each critical thinking skill indicator is presented in Figure 4.

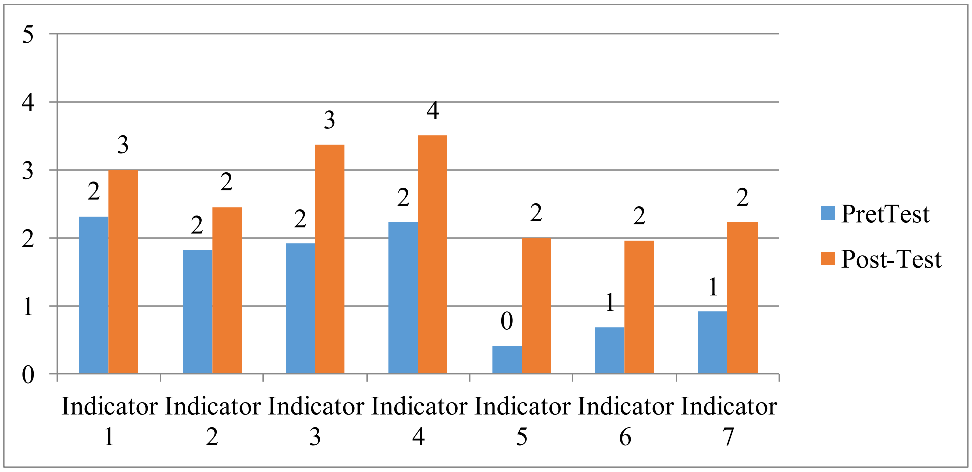

Figure 4. Average pre-test and post-test scores

Based on Figure 4, the overall average critical thinking skill score increased from 10.27 in the pre-test to 18.50 in the post-test. Improvements were also observed across all critical thinking skill indicators specifically (1) focusing on a question, (2) analyzing arguments, (3) asking and answering questions of clarification and challenge, (4) inducing and judging inductions, (5) deciding on an action (6) judging the credibility of a source, (7) definitional strategy. Improvements across all indicators suggest that implementing the Discovery Learning model supported by a covalent bond simulator has the potential to foster the development of students' critical thinking skills. Consistent with the research findings of (Simanjuntak et al., 2026), integrating a simulator with the Discovery Learning model has been shown to enhance the quality of student learning outcomes.

Indicator "Inducing and judging inductions" showed a relatively higher score increase compared to the other indicators. This progress can be credited to the feedback covalent bonding simulator, which allowed students to experiment with various bonding configurations, analyze their consequences, and form logical inferences based on the simulation's data. Furthermore, the use of a covalent bonding simulator helps students visualize abstract concepts such as electron configuration, the formation of Lewis structures, and molecular polarity. Beyond serving as a visualization tool, the simulator enables students to analyze relationships between variables, evaluate observations, and formulate logical predictions and conclusions based on available evidence (Wahidin et al., 2025). This activity aligns with the characteristics of the Discovery Learning paradigm, which encourages students to actively participate in the process of discovering and creating knowledge through inquiry and research (Burner, 1961; Martanisa et al., 2025).

In comparison to the other measures, the "assessing the credibility of a source" metric demonstrated a comparatively lesser improvement. This could also be because the learning activities were more concerned with forming correct Lewis structures and explaining bonding processes than with determining the dependability of the information used to support their responses. This result is probably due to the fact that evaluating different information sources was not a significant part of the learning activities. (Redhana, 2024) asserts that before utilizing evidence as a foundation for arguments, people must critically review its quality, validity, and relevance in order to determine the credibility of the source. Additionally, the results of the interviews showed that students felt that there was not enough time to finish the seven essay questions, which resulted in a lack of thoroughness when analyzing questions that required deeper reasoning. They also reported a decline in concentration due to fatigue after the lesson.

A covalent bond simulator application is used to evaluate students' critical thinking skills both before and after the learning process, an analysis of their pre-test and post-test scores was conducted. This analysis provides preliminary information regarding trends in critical thinking skill scores, covering the mean, score range, and data distribution. The results of this analysis subsequently serve as a basis for examining changes in student abilities following the instruction. The results of the descriptive statistical analysis are presented in Table 2.

Table 2. Pre-test and post-test descriptive statistics

Assessment	Average	Median	Minimum	Maximum	Standard Deviation
Pre-Test	10.2727	10.0000	1.0000	19.0000	5.6752
Post-Test	18.5000	18.5000	7.0000	28.0000	4.4374

Based on Table 2, research data were obtained from 22 students who participated in the entire sequence of research activities, from the pre-test to the post-test. The ideal maximum score achievable on both the pre-test and post-test was 30. The students' average critical thinking skill score increased from 10.27 on the pre-test to 18.50 on the post-test. When compared to the ideal maximum score, the pre-test average was equivalent to 34.24% of the maximum score, whereas the post-test average reached 61.67%. Similarly, the median score climbed from 10.00 in the pre-test to 18.50 in the post-test, demonstrating that students' critical thinking skills improved not only in the mean score but also in the central tendency of their performance. These results indicate that, following instruction using the covalent bond simulator application, the students' critical thinking skills showed a improvement. Students' critical thinking abilities can therefore be improved by using a simulator (Nafisa Salsabila et al., 2024) in conjunction with the discovery learning paradigm (Pertiwi et al., 2025).

In terms of the score range, the minimum score rose from 1 on the pre-test to 7 on the post-test. This finding indicates that students with the lowest initial proficiency also showed improvement following the instruction. Meanwhile, the maximum score increased from 19 to 28. The gains in both metrics demonstrate that the development of critical thinking skills occurred across various levels of student ability, encompassing both those with low initial proficiency and the highest-achieving students.

Furthermore, the standard deviation decreased from 5.68 in the pre-test to 4.44 in the post-test. This reduction indicates that the variation in critical thinking skill scores among students narrowed following the instruction compared to the baseline. Thus, instruction utilizing the covalent bond simulator application not only led to an increase in average critical thinking skill scores but also tended to foster a more uniform level of proficiency among students. Although individual variances exist, the decreased standard deviation implies that students' critical thinking skills were more uniformly distributed at the post-test. sistent with the findings of (Machfudin et al., 2025), the simulator bridges students' understanding of abstract chemical concepts, thereby minimizing the achievement gaps often observed in conventional instruction.

Subsequently, use normality to determine whether data pre-test and post-test are distributed normally. The Shapiro-Wilk test was employed to assess data normality because the sample size consisted of fewer than 50 participants (Mishra et al., 2019). The results of the normality test showed that:

Table 3. Shapiro-Wilk statistical test

Assessment	Statistic	df	Sig.
Pre-test	0.929	22	0.116
Post-test	0.971	22	0.735

Based on the decision-making criteria, a significance value exceeding 0.05 was used as the criterion for determining that the data were normally distributed (Siregar, 2026). The analysis results show significance values of 0.116 (> 0.05) for the pre-test and 0.735 (> 0.05) for the post-test; thus, both data groups satisfy the assumption of normality. As a result, both pre-test and post-test data may be interpreted as having a normal distribution.

The higher significance value of the post-test compared to the pre-test indicates that the distribution of learning outcome data following instruction tends to approximate a normal distribution more closely. Since the normality assumption was satisfied, the data were deemed appropriate for further analysis using the paired-samples t-test to examine differences in students' critical thinking skills before and after the implementation of Discovery Learning supported by the covalent bond simulator.

Table 4. Paired t-test

Pair	Mean	SD	SE	95% Conf. Interval		t	df	Sig.
				Lower	Upper			
Pre – Post Test	-8.2272	5.9596	1.27060	-10.8696	-5.5849	-6.475	21	2.04 E-06

Based on the Paired Sample t-Test results, a significance value (Sig. 2-tailed) of 2.04E-06 was obtained, which is lower than the significance level of 0.05 (0.000 < 0.05). Consequently, H_0 is rejected and H_1 is accepted, indicating a significant difference between pre-test and post-test scores following the implementation of the Discovery Learning model assisted by a covalent bond simulator application. Students' post-test scores were 8.23 points higher than their pre-test scores, with a mean difference of -8.2272 between the two. Furthermore, the 95% confidence interval for this mean difference extends from -10.8696 to -5.5849. Because this interval does not include zero, it gives more proof that the observed difference is statistically significant. A t-value of -6.475 with 21 degrees of freedom indicates that the difference between pre-test and post-test scores is greater than what could be attributed to chance variation, reinforcing the statistical evidence that students' critical thinking skill scores improved after the instructional intervention. These results suggest that the implemented instruction contributed to improving students' critical thinking skills.

The features of the Discovery Learning paradigm, which empower students to actively discover problems, collect and analyze information, validate concepts, and make judgments based on knowledge gathered, are responsible for this growth. This process aligns with (Bruner, 1961) view that discovery learning encourages students to actively construct their own knowledge, thereby fostering a more meaningful understanding. Furthermore, visualizations provided via the covalent bond simulator (Almur & Ashari, 2026), combined with guiding questions in the Student Worksheet, helped students grasp abstract concepts and connect the information they acquired in a more systematic (Noprianti et al., 2026). These findings are further supported by reflection results indicating that the majority of students felt the learning process aided their comprehension of the material and helped them articulate the reasoning behind their chosen answers.

Table 5. Effect Size Cohen's D Test

Comparison	Mean Pre-Test	Mean Post-Test	SD Diff.	Cohen's *d*	Interpretation
Pre – Post Test	10.2727	18.5000	5.9596	1.3805	Large effect

In addition to the paired t-test, the magnitude of the change was assessed using Cohen's d effect size. The research produced an effect size of 1.3805, which falls into the "large effect" category because it is above the 0.80 threshold specified by Cohen (Sullivan & Feinn, 2012). These data show that the improvement in critical thinking scores after instruction was not only statistically significant but also had major practical implications. Thus, the integration of a covalent bond simulator with the Discovery Learning paradigm significantly improved critical thinking skills among the study's participants.

Ennis's critical thinking indicators are used to assess improvements in critical thinking skills. Prior to the significance test, the normality of the pre-test and post-test scores for each critical thinking skill indicator was assessed using the Shapiro-Wilk test. The test results indicated that all indicators had significance values of less than 0.05, meaning the data were not normally distributed. Consequently, the analysis proceeded using the Wilcoxon Signed-Rank Test to determine the significance of the difference between pre-instruction and post-instruction scores (Mardiah et al., 2025). The analysis results are presented in Table 6.

Table 6. Wilcoxon test for each critical thinking skill indicator

Critical Thinking Skill Indicator	Sig. (2-tailed)	Explanation
– Focusing on a question	0.0160	Increase
– Analyzing arguments	0.0394	Increase
– Asking and answering questions of clarification and challenge	0.0003	Increase
– Inducing and judging inductions	0.0003	Increase
– Deciding on an action	0.0039	Increase
– Judging the credibility of a source	0.0046	Increase
– Definitional strategy	0.0012	Increase

Based on Table 6, all critical thinking skill indicators have a significance value (p-value) of less than 0.05. These findings indicate that the implementation of the Discovery Learning model supported by a covalent bond simulator application had a positive effect on the improvement of each indicator of students' critical thinking skills. This finding is consistent with previous studies showing that Discovery Learning can promote critical thinking in chemistry learning by actively engaging students in identifying problems, exploring information, analyzing evidence, and constructing conclusions (Martanisa et al., 2025; Pertiwi et al., 2025). The integration of digital simulations can further support this process by providing interactive and visual learning experiences that facilitate conceptual understanding and analytical engagement (Salsabila et al., 2024; Wahidin et al., 2025).

The indicator of focusing on a question yielded a significance value of 0.0160. The improvement in this indicator can be associated with the stimulation and problem statement stages, which guided students to identify relevant information and formulate problems based on the phenomena presented. Through guiding questions in the student worksheets and exploration activities within the simulator, students were trained to focus on the relationships among electron configuration, valence electrons, and the formation of Lewis structures before determining solutions to the problems. This learning process is consistent with the characteristics of Discovery Learning, in which students are encouraged to identify problems and independently construct understanding through exploration and discovery (Pertiwi et al., 2025). In the context of covalent bonding, Discovery Learning supported by digital chemical representations has also been reported to improve students' conceptual understanding (Syawal et al., 2022). Reflection results also indicated that the majority of students found the presentation of phenomena and the application's instructions helpful, making it easier for them to understand the problems posed.

The indicator of analyzing arguments yielded a significance value of 0.0394. This improvement indicates that students became increasingly capable of connecting various pieces of information and constructing reasoning based on the concepts they had learned. This ability developed as students were tasked with analyzing the formation of Lewis structures, determining the appropriate type of bond, and evaluating atomic stability based on the octet rule. Analytical activities conducted using the simulator and student worksheets encouraged students to provide justifications for their selected answers. Interactive simulations are particularly useful for supporting conceptual and analytical processes because they enable learners to observe scientific representations and examine relationships among concepts more explicitly (Wahidin et al., 2025). These findings are also supported by students' reflections indicating that simulator visualizations helped them gain a clearer understanding of the relationships among concepts.

The indicator of asking and answering clarification and challenge questions yielded a significance value of 0.0003. This result indicates that the learning process provided students with opportunities to explain, defend, and clarify the answers they obtained. During the verification and generalization stages, students did not merely determine whether a statement was correct but were also required to provide evidence and scientific reasoning to support their answers. Such activities are consistent with the development of critical thinking, which involves clarification, evaluation of reasons, and justification of conclusions (Ennis, 2011). These activities were further reinforced by reflective questions in the student worksheets that encouraged students to communicate the results of their analyses. Studies involving simulation-based science learning similarly indicate that interactive simulations provide opportunities for deeper analysis and critical engagement with scientific information (Nafisa Salsabila et al., 2024).

The indicator of determining a course of action yielded a significance value of 0.0039. Improvement in this indicator demonstrates that students became increasingly capable of identifying appropriate solution steps based on the information gathered during learning. Through the use of the simulator and student worksheets, students practiced selecting suitable strategies, such as determining the number of electron pairs required or identifying the type of bond that enables an atom to achieve stability. Discovery-oriented learning encourages students to actively select and apply strategies in solving problems rather than merely receiving predetermined solutions (Pertiwi et al., 2025). Reflection results indicated that the structured, step-by-step learning process helped students solve problems more systematically.

The indicator of inducing and assessing induction outcomes yielded a significance value of 0.0003. These results demonstrate that students became increasingly capable of drawing conclusions based on data and evidence gathered during the lesson. This ability developed through the data processing, verification, and generalization stages, which guided students to process information, verify answers, and formulate conclusions regarding bond formation and molecular polarity. This process is consistent with inquiry-oriented scientific problem solving, in which learners are required to connect evidence, concepts, and reasoning to formulate defensible conclusions (Tan et al., 2023). Reflection results further indicated that the activity of formulating conclusions helped students understand the relationships among the concepts being studied.

The indicator of assessing the credibility of a source yielded a significance value of

0.0046. This result indicates that students' ability to evaluate the accuracy of information improved following the learning process. This skill was cultivated as students compared information obtained from the simulator, teaching modules, and student worksheets before determining the most appropriate answer. Evaluating information and determining the credibility of sources constitute important dimensions of critical thinking, particularly when learners must decide whether available information is sufficiently reliable to support a conclusion (Ennis, 2011). However, progress on this indicator was not as optimal as on some other indicators, which may be explained by students' limited opportunities to independently evaluate multiple external information sources. This interpretation is also consistent with findings that limited opportunities for information evaluation and in-depth discussion can constrain the development of critical thinking skills (Salsabila et al., 2024).

The defining strategy indicator yielded a significance value of 0.0012. Improvement in this indicator demonstrates that students became increasingly capable of explaining and defining concepts based on observations and analyses conducted during the lesson. Exploration activities utilizing the simulator and guiding questions within the student worksheets helped students reorganize the information they acquired, enabling a more meaningful understanding of concepts such as atomic stability, covalent bonding, and molecular polarity. Digital representations are particularly valuable in chemical bonding because many bonding concepts involve abstract and submicroscopic entities that are difficult to understand through symbolic representations alone. Discovery Learning supported by chemical visualization has previously been shown to improve students' understanding of covalent bonding concepts (Syawal et al., 2022). More broadly, digital simulation environments can strengthen conceptual understanding by providing interactive and visual representations of scientific phenomena (Wahidin et al., 2025).

These findings indicate that the implementation of a covalent bond simulator application integrated into the Discovery Learning model not only contributed to students' critical thinking skills in general but also supported the development of specific aspects of critical thinking as reflected in Ennis's indicators. This interpretation is supported by previous research demonstrating the potential of Discovery Learning to improve critical thinking in chemistry education (Martanisa et al., 2025; Pertiwi et al., 2025), as well as studies showing that digital simulations can facilitate critical analysis, interaction, and conceptual understanding (Salsabila et al., 2024; Wahidin et al., 2025). Furthermore, the use of Discovery Learning with digital chemical representations has been reported to facilitate understanding of covalent bonding, supporting the appropriateness of this approach for advanced chemistry learning (Syawal et al., 2022).

CONCLUSION

The findings of this study indicate that the integration of a feedback-based covalent bond simulator within the Discovery Learning model was associated with a meaningful improvement in students' critical thinking skills in learning covalent bonding. The mean critical thinking score increased from 10.27 in the pre-test, equivalent to 34.24% of the maximum score, to 18.50 in the post-test, equivalent to 61.67% of the maximum score. The paired-samples t-test confirmed a statistically significant difference between the pre-test and post-test scores, $t(21) = -6.475$, $p < 0.001$, with Cohen's $d = 1.3805$, indicating a large effect.

At the indicator level, significant improvements were found across all seven critical thinking indicators based on Ennis's framework, namely focusing on a question, analyzing arguments, asking and answering clarification and challenge questions, inducing and judging inductions, deciding on an action, judging the credibility of a source, and definitional strategy. These results show that the learning process supported the development of critical thinking not only in the overall score but also across specific dimensions of students' reasoning abilities.

The improvement in critical thinking skills was supported by the integration of Discovery Learning stages, simulator-based visualization, immediate feedback, and structured activities in the Student Worksheet. These learning components provided students with opportunities to identify problems, analyze information, examine relationships among concepts, justify their answers, verify ideas, determine appropriate solution strategies, and formulate conclusions in a more systematic manner. The simulator also helped students engage with abstract concepts in covalent bonding, including valence electrons, Lewis structures, bond formation, atomic stability, and molecular polarity. The findings demonstrate that the integration of a covalent bond simulator into the Discovery Learning model can support the development of students' critical thinking skills while facilitating a more structured understanding of covalent bonding concepts as a foundation for advanced chemistry learning.

RECOMMENDATION

The findings of this study suggest that the integration of a covalent bond simulator within the Discovery Learning model has promising potential to support the development of students' critical thinking skills in chemistry learning. Nevertheless, the use of a one-group pre-test–post-test design without a control group limits the strength of conclusions regarding the contribution of the intervention. Future studies are therefore recommended to employ more rigorous research designs involving control or comparison groups, larger sample sizes, and participants from different educational contexts to provide stronger and more generalizable evidence. In addition, further research could investigate the effectiveness of simulator-assisted Discovery Learning in other chemistry topics that involve abstract and submicroscopic concepts, such as molecular geometry, intermolecular forces, chemical equilibrium, and reaction mechanisms. The simulator could also be developed and evaluated as a learning tool for strengthening other higher-order thinking skills, including problem-solving, scientific reasoning, decision-making, and creative thinking. Moreover, future studies may examine how specific simulator features, such as interactive visualization, immediate feedback, progressive learning levels, and guided exploration, contribute to students' learning processes. Such investigations could provide a more comprehensive understanding of how digital simulation can be effectively integrated with Discovery Learning to support meaningful and cognitively demanding chemistry instruction.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Riani Damay Rosida	✓	✓			✓	✓		✓	✓	✓	✓		✓	
Gun Gun Gumilar	✓	✓	✓	✓	✓			✓	✓		✓	✓		✓
Miarti Khikmatun Nais		✓						✓		✓		✓	✓	✓
Ijang Rohman			✓	✓			✓					✓		✓
Muhamad Nurul Hana				✓			✓					✓		✓
Riani Damay Rosida	✓	✓			✓	✓		✓	✓	✓	✓		✓	

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this article.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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