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Optimizing Chemistry Learning Outcomes through PhET Simulations within a Discovery Learning Approach on Chemical Bonding Material

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ABSTRACT

This study aims to analyze the effect of integrating PhET simulations within a Discovery Learning approach on students' chemistry learning outcomes, particularly in the topic of chemical bonding. This research employed a quasi-experimental design using a Posttest-Only Control Group Design, involving two groups: an experimental group and a control group. The sample was selected through a simple random sampling technique, consisting of 35 students in the experimental group and 36 students in the control group. The research instrument was a validated 25-item multiple-choice test designed to measure students' learning outcomes. Data were analyzed using both descriptive and inferential statistics, with the Mann–Whitney test applied for hypothesis testing. The results indicate that the percentage of learning mastery in the experimental group was 88.57%, which is higher than that of the control group at 75%. The hypothesis testing results show that the calculated Z value exceeds the critical Z value at a significance level of 0.05, indicating a significant difference between the two groups. Therefore, it can be concluded that the use of PhET simulations within a Discovery Learning approach has a significant effect on students' chemistry learning outcomes in the topic of chemical bonding. This study implies that the integration of technology within instructional models can enhance the effectiveness of chemistry learning, particularly for abstract concepts.

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INTRODUCTION

The rapid advancement of science and technology in the 21st century has significantly transformed the educational landscape, particularly in science education such as chemistry. The integration of digital technology into teaching and learning processes is no longer optional, but rather a necessity to enhance both the quality of instruction and students' learning outcomes. Chemistry learning is widely recognized as complex due to the abstract nature of its concepts, including atomic structures, particle interactions, and chemical bonding. These abstract characteristics often hinder students from achieving a deep conceptual understanding, ultimately leading to low academic performance. In this context, interactive simulation-based technologies have emerged as a promising solution to bridge the gap between abstract concepts and their visual representations. Tools such as PhET simulations enable students to manipulate variables and directly observe phenomena in a virtual environment, thereby making learning more concrete, contextual, and meaningful. This aligns with the perspective that technology-enhanced learning environments can improve science education through dynamic and interactive visualizations (Premthaisong & Srisawasdi, 2024).

Chemistry learning fundamentally requires students to understand three levels of representation: macroscopic, submicroscopic, and symbolic. The integration of these three levels is essential for constructing a comprehensive conceptual understanding. However, in practice, students often struggle to connect these representations, particularly in abstract topics such as chemical bonding. This difficulty frequently leads to misconceptions that negatively affect learning outcomes. Previous studies indicate that limited visualization of chemical concepts is one of the primary factors contributing to students' low conceptual understanding (Rahmawati et al., 2022). Therefore, there is a need for instructional approaches that effectively facilitate the integration of these representational levels. The use of interactive simulation media, such as PhET, offers a viable alternative, as it provides visual and interactive representations of chemical phenomena, supporting deeper conceptual comprehension. Consequently, the implementation of PhET simulations has the potential to improve students' learning outcomes in complex chemistry topics.

PhET simulations have been extensively implemented in science education and have demonstrated positive effects on students' conceptual understanding and academic performance. These simulations provide an interactive learning environment that allows students to explore concepts independently, test hypotheses, and construct knowledge through direct experience. Empirical evidence suggests that PhET-based learning significantly enhances students' conceptual understanding and academic achievement (Ibrahim et al., 2025). Furthermore, active engagement during simulation-based learning contributes to improved retention of concepts. One of the key advantages of PhET simulations lies in their ability to visualize abstract phenomena that are otherwise difficult to observe in real-life contexts. Thus, PhET functions not only as an instructional medium but also as a cognitive tool that supports knowledge construction. However, the effectiveness of such technology largely depends on the instructional strategies employed; without an appropriate pedagogical framework, its impact may not be optimal.

One instructional approach that is highly relevant for optimizing the use of PhET simulations is Discovery Learning. This model emphasizes students' active involvement in discovering concepts through exploration, observation, and analysis. In Discovery Learning, students are not passive recipients of information but actively construct their knowledge through meaningful learning experiences. Research has shown that the implementation of Discovery Learning is effective in improving students' academic performance and higher-order thinking skills (Simanjuntak & Silalahi, 2022). Moreover, this model aligns with constructivist principles, which assert that knowledge is actively constructed through interaction with the learning environment. Therefore, integrating Discovery Learning with PhET simulations presents a promising approach to enhancing the quality of chemistry learning.

The integration of PhET simulations within the Discovery Learning framework provides students with opportunities to explore concepts more deeply. In this approach, PhET serves as a virtual experimental tool, while Discovery Learning offers a structured pedagogical framework to guide the learning process. Previous studies indicate that combining inquiry-based learning with PhET simulations can significantly enhance students' critical thinking skills and conceptual understanding (Nasar et al., 2025). Additionally, this integration fosters greater student engagement, which positively impacts learning outcomes. Thus, the combination not only improves conceptual mastery but also promotes analytical and critical thinking abilities. This highlights that the effective use of technology in education must be supported by appropriate pedagogical strategies to achieve optimal outcomes.

Despite the growing body of research supporting the effectiveness of PhET simulations and Discovery Learning independently, there remains a lack of studies that specifically examine their integration in the context of chemical bonding. Most existing studies focus on other topics, such as chemical equilibrium or electricity, providing limited insight into the effectiveness of this integrated approach for chemical bonding material. This topic is particularly challenging due to its abstract and complex representational nature. Furthermore, there is a scarcity of studies that specifically investigate the impact of integrating PhET simulations and Discovery Learning on students' learning outcomes without incorporating additional variables such as motivation or attitudes. This indicates the existence of a research gap that necessitates further investigation.

In addition, previous research has highlighted that the effectiveness of PhET simulations is strongly influenced by the instructional strategies applied. The use of PhET without an appropriate pedagogical approach tends to yield suboptimal results in improving learning outcomes (Aliyu, 2025). Therefore, a structured and systematic learning model is required to maximize its potential. Discovery Learning offers a relevant alternative, as it facilitates active student engagement through guided discovery processes. However, studies integrating these two approaches comprehensively within secondary school chemistry contexts remain limited. This underscores the importance of conducting in-depth research on the integration of PhET simulations and Discovery Learning to enhance students' learning outcomes.

Based on the aforementioned discussion, this study presents novelty by specifically examining the effect of integrating PhET simulations within a Discovery Learning approach on students' chemistry learning outcomes in the topic of chemical bonding. This research not only evaluates the effectiveness of technology-enhanced learning but also integrates it with a constructivist instructional model centered on student activity. Furthermore, it contributes to addressing the existing research gap concerning the integration of instructional media and pedagogical models within specific chemistry topics. Therefore, this study is expected to provide both theoretical and practical contributions to the development of technology-based chemistry education.

Accordingly, the research question of this study is formulated as follows: *"Does the implementation of PhET simulations within a Discovery Learning approach significantly affect students' learning outcomes in chemistry, particularly on the topic of chemical bonding?"*

LITERATURE REVIEW

Chemistry Learning and the Characteristics of Chemical Bonding Material

Chemistry learning is recognized as a complex domain due to the abstract nature of its concepts, which are not directly observable. Understanding chemical concepts requires students to integrate three levels of representation: macroscopic, submicroscopic, and symbolic. These representations must be comprehended simultaneously to enable students to construct a coherent and comprehensive understanding. However, in practice, many students encounter difficulties in linking these levels, which consequently leads to low learning outcomes (Rahmawati et al., 2022).

These challenges become more pronounced in topics that are inherently abstract, such as chemical bonding. This topic requires students to analyze interatomic interactions, electron distribution, and molecular formation, all of which cannot be directly observed. Previous studies indicate that students' difficulties in chemistry are largely attributed to limitations in visualizing phenomena at the submicroscopic level (Ardila et al., 2025). As a result, misconceptions frequently arise, negatively affecting students' understanding and academic performance.

Furthermore, the characteristics of chemistry learning demand higher-order thinking skills. Students are not only required to memorize concepts but also to analyze, evaluate, and apply them in various contexts. Therefore, instructional approaches that facilitate deep and meaningful learning are essential to support students in achieving a comprehensive understanding of chemical concepts.

Discovery Learning Model in Chemistry Education

Discovery Learning is a student-centered instructional model that emphasizes the process of knowledge construction through active exploration and inquiry. In this model, students are encouraged to discover concepts independently through a series of structured activities, including stimulation, problem identification, data collection, data processing, verification, and conclusion drawing.

The implementation of Discovery Learning in chemistry education has been shown to be effective in improving students' learning outcomes. Empirical studies indicate that this model significantly enhances both academic achievement and science process skills (Simanjuntak & Silalahi, 2022). This effectiveness is attributed to students' active involvement in the learning process, which promotes deeper conceptual understanding.

In addition, Discovery Learning contributes to the development of higher-order thinking skills. A meta-analysis study demonstrates that this model has a significant impact on improving students' higher-order cognitive abilities in chemistry learning (Ardila et al., 2025). These findings suggest that Discovery Learning is not only effective in enhancing learning outcomes but also in fostering students' cognitive development.

However, the implementation of Discovery Learning in chemistry classrooms may face challenges, particularly due to the limited availability of instructional media that can effectively support conceptual exploration. Therefore, integrating appropriate learning media is necessary to optimize the effectiveness of this model.

PhET Simulations as Interactive Learning Media

PhET (*Physics Education Technology*) simulations represent a technology-based learning medium designed to facilitate students' understanding of scientific concepts through interactive visualization. These simulations allow students to explore, manipulate variables, and observe phenomena directly within a virtual environment.

The use of PhET simulations in chemistry education has been proven to enhance students' conceptual understanding and academic performance. Research findings indicate that PhET simulations significantly improve students' learning outcomes by providing interactive and concrete learning experiences (Ibrahim et al., 2025). Compared to conventional instructional methods, simulations offer a more engaging and effective way to present complex concepts.

Moreover, PhET simulations help address common misconceptions in chemistry learning. Through dynamic visualizations, students can observe processes occurring at the submicroscopic level, which facilitates a deeper understanding of abstract concepts (Rahmawati et al., 2022). This capability is particularly important in topics such as chemical bonding, where visualization plays a crucial role.

Further studies also highlight that the effectiveness of PhET simulations is maximized when integrated with appropriate pedagogical approaches, such as inquiry-based or discovery-based learning (Aliyu, 2025). This suggests that technology alone is insufficient; it must be complemented by suitable instructional strategies.

Integration of PhET Simulations in Discovery Learning

The integration of PhET simulations within the Discovery Learning framework represents a promising approach to improving the quality of chemistry education. In this context, PhET simulations serve as tools for conceptual exploration, while Discovery Learning provides a structured pedagogical framework to guide the learning process.

Previous studies demonstrate that combining simulations with inquiry- or discovery-based approaches significantly enhances student engagement and conceptual understanding (Nasar et al., 2025). Through virtual experimentation, students are able to explore phenomena that may not be feasible in real laboratory settings, making the learning process more meaningful and engaging.

Additionally, technology-supported inquiry environments provide opportunities for students to learn actively and independently, thereby promoting deeper conceptual understanding (Premthaisong & Srisawasdi, 2024). This integration aligns with constructivist learning theory, which emphasizes that knowledge is constructed through interaction with the learning environment.

Thus, the integration of PhET simulations within Discovery Learning creates a conducive learning environment that supports active knowledge construction and meaningful learning experiences.

Learning Outcomes in Chemistry Education

Learning outcomes serve as a primary indicator of the effectiveness of the instructional process. In chemistry education, learning outcomes encompass not only conceptual mastery but also the ability to apply knowledge in various contexts. These outcomes are influenced by multiple factors, including instructional models, learning media, and student engagement.

Research indicates that the use of interactive learning media, such as PhET simulations, significantly improves students' learning outcomes (Ibrahim et al., 2025). Similarly, the implementation of Discovery Learning has been shown to enhance students' academic achievement (Simanjuntak & Silalahi, 2022). Therefore, the combination of appropriate instructional models and media can yield positive impacts on learning outcomes.

Furthermore, optimal learning outcomes are achieved when students are actively engaged in the learning process. Active participation enables students to construct deeper conceptual understanding, leading to improved academic performance. Consequently, innovative instructional strategies that enhance student engagement such as the integration of technology—are essential in modern education.

METHODOLOGY

This study employed a quasi-experimental research design aimed at analyzing the effect of integrating PhET simulations within a Discovery Learning approach on students' chemistry learning outcomes, particularly in the topic of chemical bonding. The study involved two groups, namely an experimental group and a control group, each receiving different instructional treatments. The experimental group was taught using PhET simulations integrated into the

Discovery Learning model, whereas the control group received instruction using the Discovery Learning model without the support of PhET simulations. This comparative approach was adopted to examine the effectiveness of simulation-based media in enhancing students' learning outcomes.

The research design applied in this study was the Posttest-Only Control Group Design. In this design, both groups were not administered a pretest but were directly subjected to different treatments, followed by a posttest to measure learning outcomes. The selection of this design was intended to eliminate the potential influence of pretest exposure on students' performance, thereby providing a more objective evaluation of the treatment effects. Consequently, any observed differences in learning outcomes can be directly attributed to the instructional interventions applied to each group.

The population of this study comprised all eleventh-grade students enrolled in the chemistry specialization track during the 2025/2026 academic year, consisting of six parallel classes. The sampling technique employed was simple random sampling, ensuring that each class had an equal probability of being selected without consideration of specific characteristics. Based on this technique, two classes were selected as the research sample: one class as the experimental group consisting of 35 students, and another as the control group consisting of 36 students. The study was conducted during the first semester of the 2025/2026 academic year, aligned with the implementation of the chemical bonding topic in the curriculum.

The research instrument utilized in this study was a learning achievement test consisting of 25 multiple-choice items. The instrument was designed to measure students' cognitive abilities in chemical bonding, including conceptual understanding, analysis of bond formation processes, and the application of concepts in various contexts. Prior to its implementation, the instrument underwent content validity testing by experts to ensure alignment with learning indicators, as well as item validity testing to determine the accuracy of each item in measuring learning outcomes. Additionally, reliability testing was conducted to ensure the consistency of the measurement results.

The research procedure was carried out in three main stages: preparation, implementation, and evaluation. During the preparation stage, the researcher developed instructional materials, including lesson plans, student worksheets, and PhET simulation media tailored to the chemical bonding topic. In the implementation stage, the experimental group received instruction following the phases of Discovery Learning, which included stimulation, problem identification, data collection through PhET simulation exploration, data processing, verification, and conclusion drawing. Students actively interacted with the simulations to observe chemical bonding phenomena in a visual and interactive manner. In contrast, the control group was taught using the same Discovery Learning model but without the use of PhET simulations, relying instead on teacher explanations and conventional learning resources. In the evaluation stage, both groups were administered a posttest to assess their learning outcomes.

The learning outcome data, obtained in the form of raw scores, were converted into standardized scores using the formula:

Score = (number of correct answers / maximum score) × 100

Descriptive statistical analysis was then conducted to summarize students' learning outcomes, including mean scores, highest and lowest scores, and the percentage of learning mastery. Students were considered to have achieved mastery if they obtained a score of ≥ 75. The study was considered successful if at least 80% of students achieved learning mastery. Inferential statistical analysis was conducted to test the research hypothesis. Prior to hypothesis testing, prerequisite tests were performed, including tests of normality and homogeneity. If the data were not normally distributed, a non-parametric test, specifically the Mann–Whitney test, was employed to examine differences in learning outcomes between the experimental and control groups. Hypothesis testing was conducted at a significance level of 0.05.

The hypothesis of this study states that there is a significant effect of integrating PhET simulations within a Discovery Learning approach on students' chemistry learning outcomes in the topic of chemical bonding. If the significance value obtained is less than 0.05, the alternative hypothesis is accepted, indicating that the treatment has a statistically significant effect on students' learning outcomes.

RESEARCH RESULT

General Description of Research Subjects

This study involved two groups of eleventh-grade students enrolled in the chemistry specialization track, namely the experimental group and the control group. The experimental group consisted of 35 students, while the control group comprised 36 students. Both groups were selected using a simple random sampling technique, ensuring relatively equivalent characteristics prior to the implementation of the treatment. The study was conducted during the first semester of the 2025/2026 academic year, focusing on the topic of chemical bonding. The experimental group received instruction through the integration of PhET simulations within the Discovery Learning approach, whereas the control group was taught using the Discovery Learning model without the support of PhET simulations. At the end of the instructional process, both groups were administered a posttest to measure students' cognitive achievement on the learning material.

Descriptive Statistical Analysis of Learning Outcomes

Descriptive statistical analysis was conducted to provide an overview of students' learning outcomes in both groups. The results indicate that the experimental group achieved higher learning outcomes compared to the control group. This difference is reflected in several statistical indicators, including mean scores, the number of students achieving mastery, and the overall score distribution.

Based on the classification of learning outcomes according to the minimum mastery criterion (MMC) of 75, the individual mastery results are presented in Table 1.

Table 1. Students' Learning Mastery

Category	Score	Experimental (f)	Experimental (%)	Control (f)	Control (%)
Mastery	≥75	31	88.57	27	75
Non-mastery	<75	4	11.43	9	25
Total		35	100	36	100

As shown in Table 1, 31 students (88.57%) in the experimental group achieved learning mastery, while 4 students (11.43%) did not. In contrast, 27 students (75%) in the control group achieved mastery, and 9 students (25%) did not. These findings indicate that the experimental group demonstrated a higher level of learning mastery compared to the control group.

Learning Mastery Based on Indicators

In addition to overall mastery, further analysis was conducted for each learning indicator to provide a more detailed understanding of students' conceptual achievement. The results are presented in Table 2.

Table 2. Learning Mastery Based on Indicators

No	Indicator	Experimental (%)	Category	Control (%)	Category
1	Atomic stability	88.57	Mastery	80.55	Mastery
2	Ionic bond formation	97.14	Mastery	69.44	Non-mastery
3	Covalent bond formation	91.43	Mastery	80.55	Mastery
4	Types of covalent bonds	100	Mastery	80.55	Mastery
5	Molecular shape	85.71	Mastery	83.33	Mastery
6	Polarity of compounds	77.14	Non-mastery	75	Non-mastery

The data in Table 2 show that the experimental group achieved mastery in five out of six indicators, namely atomic stability, ionic bond formation, covalent bond formation, types of covalent bonds, and molecular shape. However, the indicator related to compound polarity did not reach mastery (77.14%).

In contrast, the control group achieved mastery in four indicators, while two indicators—ionic bond formation (69.44%) and compound polarity (75%)—did not meet the mastery criterion. These findings indicate that the experimental group demonstrated a higher distribution of mastery across indicators compared to the control group.

Supporting Data from Learning Worksheets (LKPD)

In addition to posttest results, students' learning outcomes were supported by their performance on student worksheets (LKPD) during the instructional process. The average LKPD scores are presented in Table 3.

Table 3. Average LKPD Scores

Meeting	Indicator	Experimental	Control
1	Atomic stability	97.7	88.2
2	Covalent bonding	99.2	89
3	Molecular shape	98	86.5

Table 3 indicates that, in each meeting, the experimental group consistently achieved higher average scores than the control group. The highest score in the experimental group reached 99.2, whereas the highest score in the control group was 89. These results suggest a consistent difference in learning performance throughout the instructional process.

Inferential Statistical Analysis of Learning Outcomes

1. *Normality Test*

The normality test was conducted using the Shapiro–Wilk test, as the sample size in each group was fewer than 50 students. The results indicated that the data in both groups were not normally distributed.

Table 4. Results of Normality Test

Group	Statistic	Sig. (α = 0.05)	Conclusion
Experimental	0.289	0.934	Not normal
Control	0.286	0.935	Not normal

These findings indicate that the assumption of normal distribution was not satisfied.

2. *Homogeneity Test*

The homogeneity test was conducted to examine the equality of variances between the two groups. The results were as follows:

F_calculated = 2.63
F_table = 1.96

Since F_calculated > F_table, it can be concluded that the variances of the two groups were not homogeneous.

3. *Hypothesis Testing (Mann–Whitney Test)*

Due to the violation of normality and homogeneity assumptions, a non-parametric Mann–Whitney test was employed to test the research hypothesis.

The results showed that:

Z_calculated = 2.15
Z_table = 1.96 (α = 0.05)

Since Z_calculated > Z_table, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted. This indicates that there is a statistically significant difference in learning outcomes between the experimental group and the control group.

DISCUSSION

The findings of this study reveal a statistically significant difference in learning outcomes between the experimental group, which was taught using PhET simulations within a Discovery Learning approach, and the control group, which was taught using Discovery Learning without simulation support. This difference is reflected in the percentage of learning mastery, where the experimental group achieved 88.57%, while the control group reached only 75%. Furthermore, the number of students who did not achieve mastery was lower in the experimental group compared to the control group. These results indicate that the integration of PhET simulations contributes positively to improving students' learning outcomes in chemistry, particularly in the topic of chemical bonding.

From a theoretical perspective, these findings can be explained by the nature of chemistry learning, which requires understanding across three levels of representation: macroscopic, submicroscopic, and symbolic. Students' difficulties in learning chemistry are often attributed to their inability to connect these three levels simultaneously. Previous studies have highlighted that chemical concepts are inherently abstract and difficult to visualize, leading to misconceptions and shallow understanding (Rahmawati et al., 2022). In this context, PhET simulations provide a significant advantage, as they offer dynamic and interactive visualizations that facilitate students' comprehension of abstract concepts such as chemical bonding.

The results of the indicator-based analysis further support these findings. The experimental group achieved mastery in five out of six indicators, whereas the control group achieved mastery in only four indicators. The most notable difference was observed in the indicator of ionic bond formation, where the experimental group reached 97.14% (mastery), while the control group achieved only 69.44% (non-mastery). This suggests that PhET simulations are particularly effective in supporting students' understanding of abstract processes, such as electron transfer and atomic interactions, which cannot be directly observed. Through simulations, students are able to visualize electron movement and interatomic interactions, making the learning process more concrete and meaningful.

These findings are consistent with prior research indicating that PhET simulations significantly enhance students' conceptual understanding and academic performance (Ibrahim et al., 2025). Moreover, simulations promote active engagement by allowing students to explore concepts independently, test hypotheses, and construct knowledge through direct experience. This aligns with the principles of constructivist learning theory, which emphasize that knowledge is actively constructed through interaction with the learning environment.

In addition to the role of instructional media, the Discovery Learning approach implemented in this study also contributed to the improvement of learning outcomes. Discovery Learning emphasizes students' active involvement in the learning process through exploration, data collection, and analysis. Previous research has demonstrated that Discovery Learning effectively enhances students' academic achievement and higher-order thinking skills (Simanjuntak & Silalahi, 2022). In this study, Discovery Learning provided a structured pedagogical framework, while PhET simulations served as a tool to facilitate deeper conceptual exploration.

The integration of PhET simulations and Discovery Learning resulted in a strong pedagogical synergy. PhET simulations offered an interactive and visual learning environment, while Discovery Learning structured the learning process through systematic inquiry. Previous studies have shown that the combination of inquiry-based learning and simulations can improve both conceptual understanding and higher-order thinking skills (Nasar et al., 2025). This indicates that the effectiveness of technology in education is significantly enhanced when supported by appropriate pedagogical approaches.

The findings are further supported by the analysis of students' worksheet (LKPD) scores, which showed that the experimental group consistently outperformed the control group across all learning sessions. This suggests that the observed differences in learning outcomes were not only evident in the final assessment (posttest) but also throughout the learning process. Students in the experimental group demonstrated higher levels of engagement and active participation, as reflected in their higher LKPD scores. The use of PhET simulations enabled students to conduct virtual experiments, observe phenomena, and draw conclusions independently, thereby enhancing their learning experience.

From the perspective of educational technology, this study reinforces the notion that integrating digital tools into instruction can significantly improve the quality of learning. Technologies such as PhET simulations create interactive and engaging learning environments that facilitate deeper conceptual understanding. Previous studies have emphasized that technology can transform students' learning experiences by providing contextualized and meaningful learning opportunities (Premthaisong & Srisawasdi, 2024). This is particularly relevant in the context of 21st-century education, which emphasizes the integration of technology in teaching and learning processes.

However, the findings also indicate that not all indicators achieved mastery in either group. The indicator related to compound polarity did not reach mastery in both the experimental and control groups. This suggests that, although PhET simulations contribute positively to learning outcomes, certain complex concepts require more intensive instructional approaches. Compound polarity involves understanding electron distribution and molecular geometry, which demand higher-order analytical skills and may require additional instructional support. The inferential statistical analysis further confirms these findings, showing a significant difference between the learning outcomes of the experimental and control groups. The calculated Z value exceeding the critical value indicates that the research hypothesis is accepted, confirming that the use of PhET simulations within a Discovery Learning approach has a significant effect on students' learning outcomes. This provides empirical evidence that the integration of instructional media and pedagogical models enhances learning effectiveness.

In terms of significance, this study contributes to the field of chemistry education, particularly in the development of technology-based instructional strategies. The findings demonstrate that the integration of PhET simulations within a Discovery Learning framework can serve as an effective alternative for improving students' learning outcomes. Moreover, this study highlights that the synergy between technology and pedagogy is a critical factor in enhancing the quality of education. The practical implications of this study suggest that teachers should optimize the use of technology in the classroom. PhET simulations can assist teachers in explaining abstract concepts and increasing student engagement. Additionally, teachers should integrate technology with appropriate instructional models, such as Discovery Learning, to ensure effective learning processes. Thus, instruction should not only focus on content delivery but also on facilitating students' active construction of knowledge.

Despite its positive findings, this study has several limitations. First, the study was limited to a single topic, namely chemical bonding, which restricts the generalizability of the findings to other topics. Second, the use of a posttest-only design does not allow for direct measurement of students' learning gains from their initial conditions. Third, the implementation of PhET simulations requires adequate technological facilities, which may limit its applicability in schools with limited resources.

Furthermore, this study did not examine other factors that may influence learning outcomes, such as students' motivation, interest, or prior knowledge. Future research is recommended to explore these variables to obtain a more comprehensive understanding of the effectiveness of technology-based learning. Additionally, future studies may develop more innovative instructional models by integrating various media and pedagogical approaches.

Overall, the results of this study indicate that the use of PhET simulations within a Discovery Learning approach has a positive effect on students' chemistry learning outcomes. The integration of appropriate instructional media and pedagogical models enhances conceptual understanding, student engagement, and overall learning performance. Therefore, the use of technology in chemistry education should continue to be developed to improve the quality of education in the future.

CONCLUSIONS

Based on the findings, the integration of PhET simulations within a Discovery Learning approach significantly affects students' chemistry learning outcomes on chemical bonding. This is evidenced by higher learning mastery and better indicator achievement in the experimental group compared to the control group. Inferential analysis using the Mann–Whitney test confirms a significant difference between the two groups (Zcount > Ztable at $\alpha = 0.05$), indicating that the research hypothesis is accepted. Overall, the use of PhET simulations in Discovery Learning creates a more interactive learning environment and enhances students' understanding of abstract concepts, leading to improved academic performance.

RECOMMENDATIONS

Based on the findings, the integration of PhET simulations within a Discovery Learning approach significantly affects students' chemistry learning outcomes on chemical bonding. This is evidenced by higher learning mastery and better indicator achievement in the experimental group compared to the control group. Inferential analysis using the Mann–Whitney test confirms a significant difference between the two groups (Zcount > Ztable at $\alpha = 0.05$), indicating that the research hypothesis is accepted. Overall, the use of PhET simulations in Discovery Learning creates a more interactive learning environment and enhances students' understanding of abstract concepts, leading to improved academic performance.

ADVANCED RESEARCH

Despite its positive findings, this study has several limitations. The use of a posttest-only design does not capture students' initial abilities or learning gains over time. The study is also limited to the topic of chemical bonding and a relatively small sample from a specific context, which restricts generalizability. Additionally, the effectiveness of PhET simulations depends on technological readiness, and this study only focused on cognitive outcomes without considering other influencing variables. Future research is recommended to use more comprehensive designs, involve broader samples and topics, and examine additional variables such as critical thinking and digital literacy to provide a more holistic understanding of technology-integrated learning.

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