

The Effectiveness of Combining Artificial Intelligence with PhET Simulations to Bridge Fundamental Physics Knowledge Gaps in Science Education for Students

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ABSTRACT

This study aims to analyze the effectiveness of integrating Artificial Intelligence (AI) and PhET simulations in improving the learning outcomes of first-semester students in the Science Education Program at Khairun University. The research employed a quasi-experimental design with a one-group pretest-posttest approach involving 28 students. The research instrument consisted of a learning achievement test, analyzed using a paired sample t-test and normalized gain (N-gain). The findings revealed a significant increase in posttest scores compared to pretest scores ($p < 0.05$), with an average N-gain categorized as medium. These results indicate that integrating AI and PhET-based learning successfully enhances students' conceptual understanding, promotes learning autonomy, and bridges the gap in fundamental physics knowledge. The study highlights the importance of employing intelligent technologies and interactive simulations as innovative strategies in 21st-century science education.

Keywords: Artificial Intelligence, PhET simulation, learning outcomes, Science Education, learning innovation, knowledge gap

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INTRODUCTION

General Physics is a core subject that equips science and engineering students with essential conceptual foundations, problem-solving skills, and analytical reasoning. However, many first-year university students in Indonesia begin this course with limited mastery of fundamental high school physics, particularly in mechanics, energy, and Newtonian concepts. This gap often results in low academic performance, reduced motivation, and higher levels of learning anxiety.

Previous studies have demonstrated the potential of emerging technologies to address such challenges. Artificial Intelligence (AI) applications in education provide adaptive, personalized learning environments by delivering real-time feedback and tailoring content to individual needs (Holmes et al., 2022; Yehya et al., 2025). Meanwhile, PhET interactive simulations have proven effective in visualizing abstract concepts, fostering engagement, and reducing misconceptions through inquiry-based exploration (Moore et al., 2014; Dy et al., 2024). Despite these benefits, most research has examined AI and PhET separately, with limited evidence on their combined use as a remediation strategy in higher education.

This research gap is particularly critical in the Indonesian context, where universities continue to face persistent disparities in students' physics readiness. To date, little is known about how

integrating AI with PhET simulations can bridge conceptual knowledge gaps and support the transition from secondary to tertiary education.

Therefore, this study investigates the effectiveness of combining AI-based learning tools and PhET interactive simulations in improving first-year students' conceptual understanding of physics. By addressing both cognitive and motivational outcomes, the study contributes to the growing body of literature on technology-enhanced science education and offers practical implications for developing adaptive, student-centered learning strategies in higher education.

METHOD

This study employed a quantitative approach with a one-group pretest–posttest design (quasi-experimental). This design was selected because the study involved only one class without a control group, yet it still allowed for the measurement of the effectiveness of the treatment provided (Creswell & Creswell, 2018). In this context, the treatment consisted of the integration of Artificial Intelligence (AI) technology and PhET simulations into the teaching of General Physics I.

The research design can be illustrated as follows:

Pretest → Treatment (AI- and PhET-based learning) → Posttest

Through this design, the researcher was able to compare students' conceptual understanding before and after the intervention. Thus, changes in learning outcome scores could be interpreted as the effect of integrating AI and PhET technology.

The research subjects were first-semester students of the Science Education Program at Universitas Khairun who enrolled in General Physics I during the odd semester of the 2025/2026 academic year. Subjects were selected purposively because this class represented the real conditions of first-year students who generally face limited mastery of basic physics concepts from senior high school. In addition, the relatively small number of students enabled better control of the learning process and more intensive observation.

Three main instruments were employed in this study:

1. **Physics Conceptual Understanding Test**

The test was in the form of multiple-choice questions with reasoning, consisting of 20 items. It covered fundamental physics topics from senior high school that are relevant to General Physics I, such as kinematics, dynamics, energy, and Newton's laws. Content validity was examined through expert judgment by three physics education lecturers, while reliability was measured using Cronbach's Alpha, with the instrument considered reliable if the coefficient was greater than 0.70 (Fraenkel & Wallen, 2019).

2. **Student Perception Questionnaire**

The questionnaire was designed to assess students' perceptions of their learning experiences with AI and PhET simulations. A five-point Likert scale was used, covering indicators such as ease of use, motivation, engagement, and perceived benefits.

3. **Learning Activity Observation Sheet**

Observations were conducted by the researcher and a teaching assistant to monitor the level of student participation during the learning process. Observation indicators included the frequency of asking questions, participation in discussions, interaction with the simulations, and the ability to connect high school physics concepts with General Physics I content.

Research Procedure

The research procedure was carried out in four main stages:

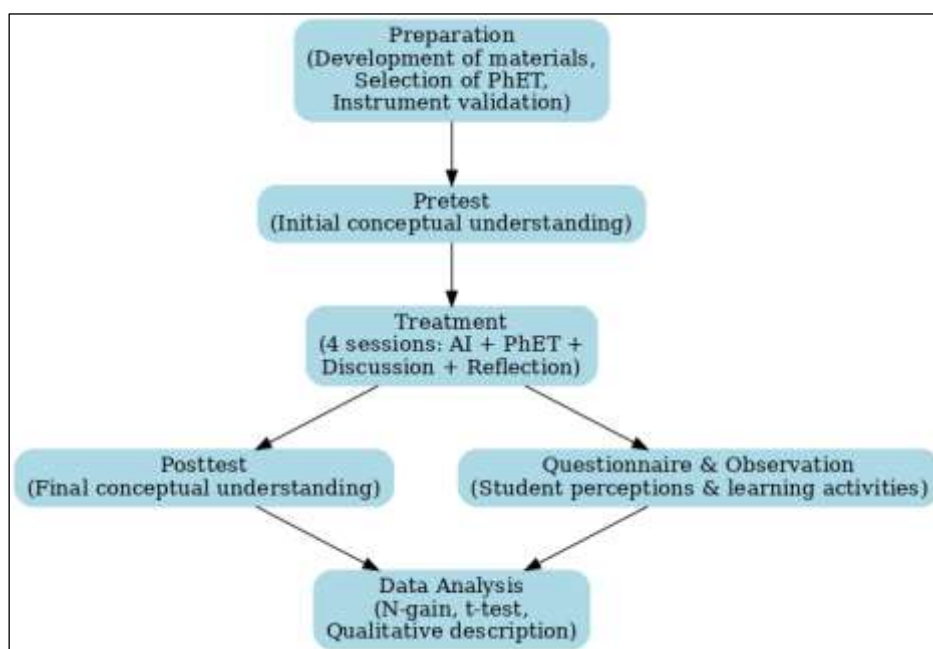


Figure 1. The research procedure

Data Analysis

Data were analyzed both quantitatively and qualitatively.

1. Quantitative Analysis

- The improvement of students' learning outcomes was analyzed using the N-gain to determine the effectiveness of the learning intervention (Hake, 1999).
- A paired sample t-test was conducted to examine the significance of the differences between pretest and posttest scores.
- All analyses were performed using SPSS version 26 with a significance level of 0.05.

2. Qualitative Analysis

- Data from the perception questionnaire were analyzed descriptively by calculating the percentage of each response category.
- Data from classroom observations were analyzed using simple coding techniques to identify patterns of student engagement.

FINDING AND DISCUSSION

This study involved first-semester students of the Science Education Program who were enrolled in the General Physics I course. Data were collected through a conceptual understanding test (pretest–posttest), perception questionnaires, and observation of learning activities.

1. Conceptual Understanding Test Results

The mean pretest score indicated a relatively low level of students' mastery of basic physics concepts (mean = 44.67; SD = 2.90). After the treatment involving the integration of AI and PhET simulations, the mean posttest score increased significantly (mean = 78.35; SD = 2.66).

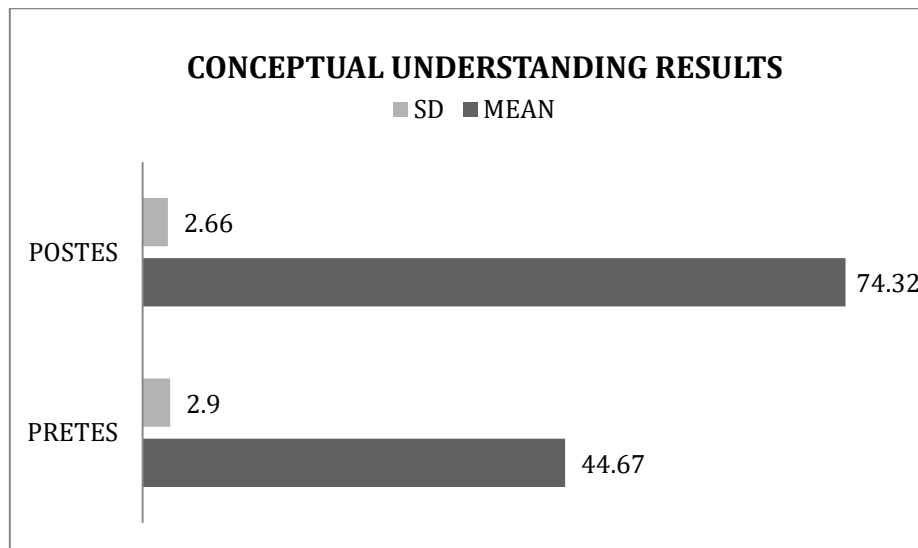


Figure 2. Conceptual Understanding Results

The N-gain calculation produced an average score of 0.61, placing it within the medium-high category (Wahab et al., 2021). The results of the paired sample t-test demonstrated a significant difference between the pretest and posttest scores ($t = 58.12$; $p < 0.001$). Consequently, the integration of AI and PhET simulations has been shown to be effective in enhancing students' fundamental understanding of physics.

Paired Samples Test

Pair	Mean Difference	Std. Deviation	t	df	Sig. (2-tailed)
Posttest – Pretest	33.68	2.85	58.12	27	0.000

Table 1. Paired Sample Test Results

2. Student Perception Questionnaire Results

The questionnaire analysis revealed that 85.7% of students felt that AI- and PhET-based learning helped them understand physics concepts that are difficult to visualize. Furthermore, 78.6% reported being more motivated to engage in independent learning, while 71.4% indicated that interaction with AI provided a more personalized learning experience due to the availability of instant feedback.

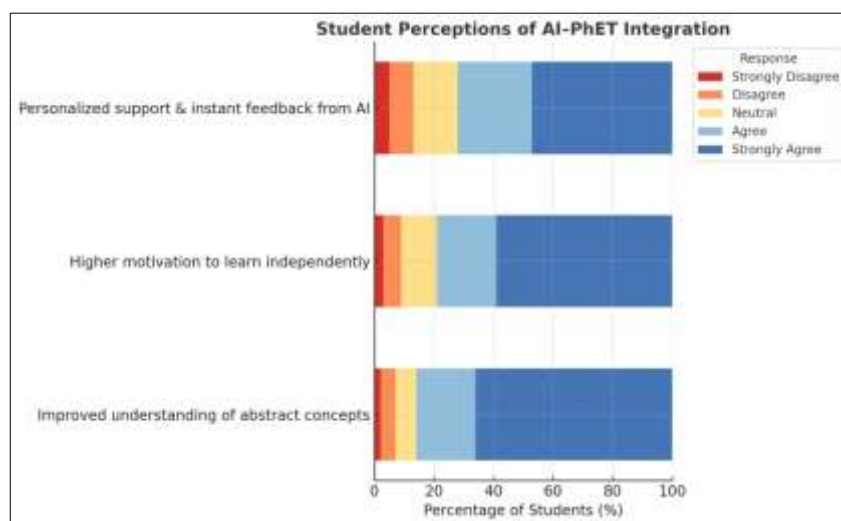


Figure 3. Student Perceptions Questionnaire Results

3. Observation of Learning Activities

Observations showed a significant increase in student engagement. In the first session, only about 35% of students actively asked questions and participated in discussions. However, by the fourth session, the participation rate had risen to 82%. Students also demonstrated greater enthusiasm when exploring concepts through PhET simulations, particularly on topics related to dynamics and energy.

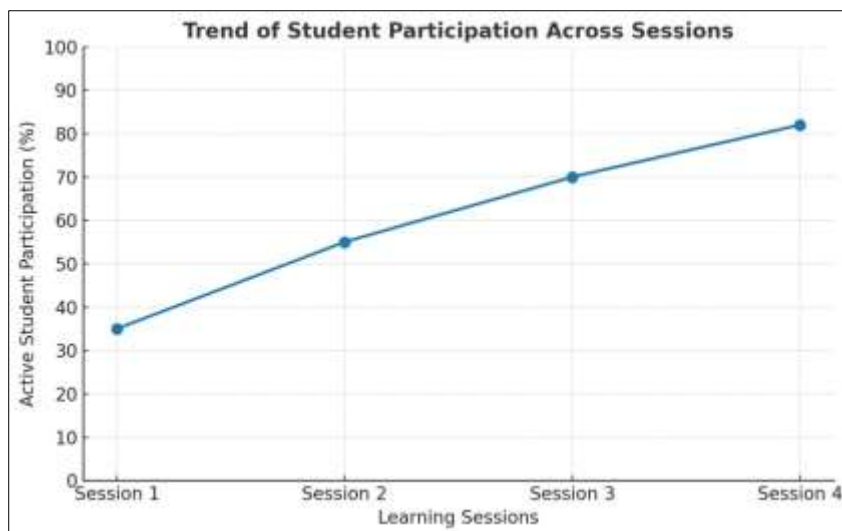


Figure 4. Student participation Across Sesion

DISCUSSION

The findings of this study confirm that the integration of Artificial Intelligence (AI) and PhET simulations effectively enhances first-year students' conceptual understanding of physics while simultaneously improving motivation and learning autonomy. The significant increase in posttest scores and medium-high N-gain value demonstrate that this integrative approach addresses one of the most persistent challenges in higher education: the lack of preparedness among incoming students in mastering fundamental concepts.

These results are consistent with prior research highlighting the benefits of AI in providing adaptive feedback and personalized learning pathways (Holmes et al., 2022; Yehya et al., 2025) and the effectiveness of PhET in visualizing abstract concepts and fostering engagement (Moore et al., 2014; Dy et al., 2024). However, this study extends the literature by showing that when these tools are combined, their complementary strengths create a synergistic effect. While AI serves as a digital tutor that diagnoses and remediates individual misconceptions, PhET contextualizes abstract principles through inquiry-based simulations. Together, they form a holistic learning environment that supports both cognitive and affective outcomes.

A critical contribution of this study lies in its Indonesian context, where disparities in students' prior physics knowledge are pronounced due to variations in secondary school curricula and limited access to laboratory facilities. Previous studies have primarily examined AI or PhET in isolation or in contexts with stronger educational infrastructures. By focusing on first-semester science education students, this study demonstrates the feasibility of technology-enhanced remediation in resource-limited settings.

Beyond cognitive gains, the results also indicate a positive shift in students' affective dimensions, including motivation and engagement. This aligns with Zhou et al. (2023), who argue that interactive technologies can cultivate curiosity and self-directed learning—skills essential in the 21st-century learning paradigm. Importantly, the increased student participation observed across sessions

suggests a gradual transformation from lecturer-centered to student-centered pedagogy, resonating with the principles of the *Merdeka Belajar–Kampus Merdeka* (MBKM) framework.

Nevertheless, several limitations should be acknowledged. The absence of a control group restricts causal inferences, and the small sample size limits generalizability. These limitations highlight the need for future research employing larger, more diverse populations and experimental designs with control groups. Additionally, long-term evaluations are required to determine whether the observed improvements in conceptual understanding and motivation are sustainable over time.

Overall, this study contributes to the ongoing discourse on digital transformation in science education. It provides empirical evidence that integrating AI and PhET simulations offers not only an effective remediation model but also a scalable approach to bridging knowledge gaps in higher education, particularly in developing contexts.

CONCLUSIONS

This study demonstrates that integrating Artificial Intelligence (AI) and PhET simulations into the *Fundamental Physics I* course effectively narrows the knowledge gap for first-semester science education students. The results of the paired-sample t-test reveal a significant difference between pretest scores ($M = 44.68$) and posttest scores ($M = 78.36$), with $p < 0.05$. Additionally, the N-Gain calculation of 0.61 indicates a medium to high level of improvement. Students also reported positive perceptions of the learning process, showing increased motivation and enhanced self-directed learning.

These findings suggest that employing intelligent technologies and interactive simulations not only addresses initial conceptual limitations but also encourages a shift toward more adaptive, contextual, and student-centered learning environments. While this study was limited to a single class with a relatively small sample size, it provides substantial empirical evidence for developing innovative learning models in higher education, particularly in facilitating the transition from secondary to tertiary education.

Suggestions

Future studies should include larger and more diverse samples to enhance the generalizability of the findings. Researchers should also explore the effectiveness of integrating AI and PhET in various physics courses and other scientific disciplines. Furthermore, the use of advanced AI systems, such as machine learning–based intelligent tutoring systems, should be considered to develop more adaptive and personalized learning pathways. Long-term evaluations are essential to assess the sustainability of the impact on academic achievement, motivation, and 21st-century skills, ensuring that this learning model can be effectively integrated into higher education curricula.

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