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The Effect of the PhET Simulation-Assisted Inquiry Model on Elementary School Students' Critical Thinking Skills and Science Literacy in IPAS Learning on Electricity

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Abstract
Science learning in elementary schools is still dominated by a lecture approach that does not encourage exploration and the use of technology. This study aims to examine the effect of the PhET Simulation-assisted inquiry learning model on students' critical thinking skills and science literacy. The study uses a quantitative approach with a nonequivalent control group quasi-experimental design. The research subjects consisted of 52 fifth-grade students divided into an experimental group and a control group. The instrument was a multiple-choice test that had been tested for validity, reliability, difficulty level, and discrimination. Data analysis used Multivariate Analysis of Covariance (MANCOVA) with the pretest as a covariate. The treatment was conducted over several structured inquiry sessions, allowing students to manipulate variables and observe scientific phenomena virtually. The results of the analysis showed a significant effect of the PhET-assisted inquiry model on critical thinking skills $F = 17.669$, $p < 0.001$, $\eta p^2 = 0.269$ and science literacy $F = 12.804$, $p = 0.001$, $\eta p^2 = 0.211$. Furthermore, qualitative observations indicated heightened student engagement and collaborative discussion during the simulation activities. These findings confirm that inquiry-based learning integrated with interactive digital media is effective in improving 21st-century skills in elementary school students. This study provides empirical evidence supporting the adoption of simulation-assisted pedagogy to bridge the gap between abstract scientific concepts and concrete understanding in primary education.

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Introduction

The transformation of the world of work and social life due to the Industrial Revolution 4.0 and Society 5.0 has required the education system to prepare students with more complex 21st-century skills. It is not enough to simply master content; students need to have critical thinking, problem-solving, collaboration, and science literacy skills to face the challenges of the digital age (Amelia, 2023; Siahaan, 2022). Kurniati and Arafah (2025) emphasizes that critical thinking is at the core of 21st-century learning because it enables students to evaluate information, construct logical arguments, and make data-driven decisions. In addition, science literacy is also an important aspect in equipping students to deal with global issues such as climate change and the energy crisis. (Kundariati, 2025; Suryati, 2025). Improving critical thinking skills and science literacy is not only a global necessity, but also a challenge for the national education system. (Maulida, 2025; Verawati & Nisrina, 2025).

In response to these global changes, Indonesia has reformed its curriculum through the Merdeka Curriculum, which emphasizes differentiated, competency-based, and contextual learning. This curriculum provides space for teachers and students to develop active learning that stimulates creativity, exploration, and the use of digital technology (Helker, 2025; Verawati & Nisrina, 2025). One important dimension in the implementation of the Merdeka Curriculum is the emphasis on strengthening the Pancasila student profile, which includes critical thinking and scientific reasoning. Investigation-based learning practices often do not work optimally in elementary schools (Gonzalez Perez, 2025; Lakew, 2025).

IPAS learning in fifth grade elementary schools in Malang City shows various obstacles based on the results of interviews and initial assessments. Teachers reported that most students had difficulty understanding electrical concepts due to a lack of visual media, limited opportunities for experimentation, and limited teaching aids and learning time. Pretest and formative assessment results also showed that student scores were below the minimum passing grade. During learning activities, students tended to be passive and not involved in the scientific exploration process. Various studies (Kastur, Kurniasari, Julianto, & Rahmawati, 2025; Wardianti, 2023) emphasizes that scientific activities such as experiments, observations, and discussions are still rarely conducted. Other obstacles include a lack of teacher training in implementing active learning strategies (Windasari, Lasmawan, & Kertih, 2024). This condition indicates that a student-centered model oriented towards the use of digital technology is needed.

The inquiry learning model is an effective model for developing critical thinking skills and understanding the scientific process. Through the stages of observation, problem formulation, hypothesis development, experimentation, and conclusion drawing, students are encouraged to actively discover concepts (Feriyanti, Yani, & Arsyad, 2025; Zidane, Putro, & Arwinda, 2025). Various studies (Gultom & Surya, 2025; Mayang, Rahmi, Yeni, & Hendri, 2025) support the effectiveness of this model, but the majority of studies still focus on junior high and high school levels. Studies on its application in science and mathematics learning at the elementary school level, especially in electricity, are still limited. In addition, there has not been much research comparing the effectiveness of types of inquiry such as guided inquiry combined with digital media.

The integration of Physics Education Technology (PhET) with an inquiry-based approach is considered to improve the effectiveness of science learning. This interactive simulation medium provides opportunities for students to conduct virtual experiments safely and in an engaging manner (Arden et al.; Parisu, Sisi, & Juwairiyah, 2025; Satriawan, 2025). However, research on the use of PhET in elementary science education, especially on abstract topics such as electrical circuits, is still very limited. Therefore, research is needed to evaluate the effectiveness of integrating inquiry models and PhET simulations in improving elementary school students' critical thinking and science literacy skills.

This study aims to determine the extent to which the PhET Simulation-assisted inquiry learning model can improve the quality of science learning, particularly in the subject of Electrical Circuits for fifth graders. This study assesses the effect of this approach on students' critical thinking skills and science literacy, considering that both are important for understanding abstract electrical concepts.

Method

This study employed a quantitative approach using a quasi-experimental method with a nonequivalent control group design, involving an experimental group and a control group with pretest and posttest measurements. The experimental group received instruction using PhET Simulation as an interactive learning medium to explore electrical circuit concepts, enabling students to independently and safely experiment with various circuit configurations, while the control group received conventional instruction without the use of PhET. The research participants consisted of all 52 fifth-grade students of SDN Bandungrejosari 4, selected through saturated sampling, with class VA (26 students) designated as the experimental group and class VB (26 students) as the control group, based on pretest results and the teacher's assessment indicating comparable initial abilities. Data were collected using multiple-choice test instruments to measure critical thinking and science literacy skills, each originally comprising 50 items and subsequently validated using Point Biserial correlation and tested for reliability using the KR-20 formula. The validation process resulted in 20 valid and reliable items for each instrument, with reliability coefficients of 0.842 for critical thinking and 0.866 for science literacy, both categorized as very good (>0.80). Item analysis showed that the critical thinking test consisted of items with varying difficulty levels (difficult, moderate, and easy), while the science literacy test predominantly comprised difficult and moderate items, and all items demonstrated acceptable to very good discrimination indices. Indicators of critical thinking and science literacy were developed based on established theoretical frameworks. The collected data were analyzed using Multivariate Analysis of Covariance (MANCOVA), with pretest scores treated as covariates, to examine the simultaneous effect of the PhET Simulation intervention on students' critical thinking and science literacy outcomes.

Results and Discussion

Results

Descriptive statistics show differences between the experimental and control groups. Students who learned using the PhET Simulation-assisted inquiry learning

model obtained higher posttest scores on both variables measured. The average critical thinking skill in the experimental group was 72.69, while science literacy reached 79.23. This difference in scores provides an initial indication that the use of interactive simulation-based inquiry can improve students' understanding and analytical skills more effectively than conventional learning.

Before conducting the MANCOVA test, a number of basic assumptions were tested and all were met. The Shapiro-Wilk normality test showed that all residual data were normally distributed ($p > 0.05$). Levene's Test of homogeneity also showed that the variances of the two groups were homogeneous, both in critical thinking ($p = 0.070$) and science literacy ($p = 0.314$). With these assumptions met, MANCOVA analysis could be performed appropriately to assess the effect of the learning model in Table 3.

Tabel 1. Multivariate Test

Effect		Value	F	Hypothesis Df	Error Df	Sig.	Partial Eta Squared
Covariatebk	Pillai's Trace	.578	32.204[b]	2.000	47.000	.000	.578
	Wilks' Lambda	.422	32.204[b]	2.000	47.000	.000	.578
	Hotelling's Trace	1.370	32.204[b]	2.000	47.000	.000	.578
	Roy's Largest Root	1.370	32.204[b]	2.000	47.000	.000	.578
Covariatels	Pillai's Trace	.551	28.804[b]	2.000	47.000	.000	.551
	Wilks' Lambda	.449	28.804[b]	2.000	47.000	.000	.551
	Hotelling's Trace	1.226	28.804[b]	2.000	47.000	.000	.551
	Roy's Largest Root	1.226	28.804[b]	2.000	47.000	.000	.551
Method	Pillai's Trace	.366	13.575[b]	2.000	47.000	.000	.366
	Wilks' Lambda	,634	13,575[b]	2,000	47,000	,000	,366
	Hotelling's Trace	,578	13,575[b]	2,000	47,000	,000	,366
	Roy's Largest Root	,578	13,575[b]	2,000	47,000	,000	,366

The MANCOVA test results show a significant effect of the learning model on both variables simultaneously. Wilks' Lambda value of 0.634 with $p < 0.001$ indicates a very significant effect, reinforced by a Partial Eta Squared (ηp^2) of 0.366, which is classified as a large effect. The PhET Simulation-assisted inquiry learning model contributes significantly to improving overall student learning outcomes.

To see the effect on each variable, a univariate test was conducted. The results showed that the learning model had a significant effect on critical thinking skills ($F = 17.669$; $p = 0.000$; $\eta p^2 = 0.269$) and science literacy ($F = 12.804$; $p = 0.001$; $\eta p^2 = 0.211$).

Both effects were large, so it can be concluded that the inquiry approach supported by interactive visual simulations is effective in improving students' analytical skills and understanding of scientific concepts. With this approach, students not only receive explanations, but also actively explore, test, and reflect on concepts through more meaningful learning experiences. The results of the univariate test are shown in Table 1.

Tabel 5. Univariate Test

Source	Variable	F	Sig.	Hp^2	Interpretation
Method	Critical Thinking	17.669	.000	0.269	Significant, Large Effect
	Science Literacy	12.804	.001	0.211	Significant, Large Effect

Covariate analysis also provides important information regarding the influence of initial values on learning outcomes. The critical thinking pretest had a significant effect on the critical thinking posttest (p = 0.000), but had no effect on science literacy (p = 0.235). Conversely, the science literacy pretest had a significant effect on the science literacy posttest (p = 0.000), but no effect on critical thinking (p = 0.241). These findings confirm that students' initial scores only affect similar variables, so the use of covariates in the analysis is necessary to ensure that the treatment effect is calculated accurately. The effect of the pretest covariate is shown in Table 6.

Tabel 2. Pengaruh Kovariat *Pretest*

Covariate	Variable	Significance	Interpretation
Pretest BK	Critical Thinking	Yes (P = 0.000)	BK Pretest Affects BK Posttest Results
	Science Literacy	No (P = 0.235)	Does Not Affect LS
Pretest LS	Critical Thinking	Yes (P = 0.000)	LS Pretest Affects LS Posttest Results
	Science Literacy	No (P = 0.241)	Does Not Affect BK

Based on the interpretation of the table, it can be seen that the critical thinking covariate has a different effect on the two dependent variables. A significance value of 0.000 (< 0.05) indicates that the critical thinking covariate has a significant effect on students' critical thinking skills, while a significance value of 0.235 (> 0.05) indicates that this covariate does not have a significant effect on science literacy. This finding indicates that students' initial critical thinking skills only affect the improvement of critical thinking skills, but do not directly contribute to the improvement of science literacy. Furthermore, the science literacy covariate also shows a similar pattern of influence. A significance value of 0.241 (> 0.05) indicates that initial science literacy does not have a significant effect on critical thinking skills, while a value of 0.000 (< 0.05)

indicates a significant effect on science literacy. Thus, it can be confirmed that students' initial scores only influence similar variables or those within the same competency domain, so that each covariate works specifically on its dependent variable.

Overall, the results of the study indicate that the use of the PhET Simulation-assisted inquiry learning model significantly improves elementary school students' critical thinking and science literacy skills. The effect is not only statistically significant, but also large in practical terms ($\eta p^2 = 0.366$). These findings indicate that students' initial scores (pretests) influence final results, particularly in similar variables. Therefore, control of important covariates influences accurate treatment. This reinforces the argument that the learning model contributes greatly to improved learning outcomes. Consistent application of the PhET Simulation-assisted inquiry model can improve both aspects of student skills, either simultaneously or separately.

Discussion

The results of the Multivariate Analysis of Covariance (MANCOVA) test show that the PhET Simulation-assisted inquiry learning model has a significant effect on improving the critical thinking and science literacy skills of elementary school students. Wilks' Lambda value of 0.634 with $p < 0.001$ and an effect of $\eta p^2 = 0.366$ indicate a strong influence. Empirically, the achievements of students in the experimental group increased significantly more than those in the control group, confirming that the use of interactive simulations helps overcome the limitations of teaching aids and provides visualizations of electrical concepts that have been difficult for elementary school students to understand, as well as enriching learning experiences and deepening students' conceptual understanding. The findings confirm that digital learning environments can encourage more active cognitive engagement.

Theoretically, the results of this study support the principle of constructivism, which emphasizes that meaningful learning occurs when students construct knowledge through direct experience (Huda, 2025; Raihan, 2025; Taqwim et al., 2025). Piaget stated that elementary school students are at the concrete operational stage, so they need visual media and manipulative activities to understand abstract concepts (Adwitiya; Wahyuni, 2025). PhET Simulation tests cause-and-effect relationships through direct interaction with electrical circuits. By assembling components, turning on switches, and observing changes in current and voltage in real time, students have the opportunity to validate their hypotheses independently.

The integration of inquiry models and digital simulations increases student activity in discussing, asking questions, and making inferences based on visual data (Li, 2025). Interactive visualizations can connect abstract concepts of electrical cycles with concrete representations, thereby strengthening students' ability to map logical relationships and develop scientific arguments.

Compared to previous studies, these results are consistent with Safitri (2025) which found that the inquiry approach is effective in improving critical thinking skills through exploration and reflection activities. The use of PhET Simulation in the inquiry model allows teachers to design learning experiences that stimulate higher-order thinking skills while increasing student motivation and curiosity. This is in line with the demands of the Merdeka Curriculum, which emphasizes exploration-based learning, problem solving, and the development of 21st-century skills (Asy'arie, 2025; Nurjanah, 2025). The inquiry process supported by digital visualization also helps students develop metacognitive skills, as they not only receive information but also process, compare, and draw conclusions from the simulation data.

However, this study has limitations in terms of the scope of the material and the location of the research. The study only focused on electrical circuit material and involved one elementary school, so generalizing the results to other materials or larger populations requires further research. Future studies could explore the integration of PhET Simulation in various IPAS sub-topics, examine the long-term effects on scientific skills, or combine it with other pedagogical approaches such as project-based learning and gamification.

Overall, the findings of this study indicate that PhET Simulation-assisted inquiry learning is a powerful and relevant approach to improving elementary school students' critical thinking and science literacy skills. With the support of significant statistical results and learning theory reinforcement, this approach can be an innovative alternative in science learning that is more active, meaningful, and contextual with the current developments in educational technology.

Conclusion

The results of the MANCOVA analysis show that the PhET Simulation-assisted inquiry learning model has a significant effect on improving the critical thinking and science literacy skills of elementary school students. This model is effective because it provides an exploratory learning experience supported by digital visualization, thereby facilitating the understanding of electrical concepts and the development of analytical skills. Further research is recommended to explore the application of this model to other science subjects and various school levels.

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findings of this study will provide meaningful contributions to the field of education, particularly in advancing the development and implementation of technology-assisted learning.

Authors' Note

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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