JPPIPA 11(11) (2025)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

A Virtual Laboratory to Improve the Effectiveness of Interactive Learning Media on Science Process Skills and Science Literacy in the Competency Aspects of Dynamic Electricity

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Received: September 20, 2025
Revised: October 27, 2025
Accepted: November 25, 2025
Published: November 30, 2025

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DOI: 10.29303/jppipa.v11i11.13531

Abstract: Implementing interactive learning media based on virtual laboratories is efficacious in improving students' scientific literacy in science learning. This study aims to assess the effectiveness of using interactive learning media based on virtual laboratories in improving students' scientific literacy and science process skills in dynamic electricity in two schools, namely SMP Negeri 1 Kwandang and MTs Al-Khairaat Kwandang, using a guided inquiry learning model. The research design employed was a quasi-experimental design with a pretest-posttest control group. Data was obtained through scientific literacy tests and observation sheets for science process skills. The study's results showed that interactive learning media based on virtual laboratories were effective in enhancing students' scientific literacy and science process skills. The results of the N-Gain analysis for scientific literacy showed an average score of 0.72, indicating a high category. Meanwhile, the results of the observations showed an increase in the achievement of science process skills at each meeting, particularly for the indicators of observing and conducting experiments, which improved to the very good category. Additionally, the results of the t-test on scientific literacy revealed a statistically significant difference ($p < 0.05$), indicating a significant difference between the pre- and post-learning periods. Thus, interactive learning media based on virtual laboratories assisted by guided inquiry models have been proven effective in improving students' scientific literacy and science process skills.

Keywords: Dynamic electricity; Learning media; Science process skills; Scientific literacy; Virtual laboratory

Introduction

The development of science and technology in the 21st century requires students to have scientific thinking skills and modern-day skills. In the context of science learning, these abilities are reflected in scientific literacy, which encompasses the ability to understand natural phenomena scientifically, interpret data, and make evidence-based decisions (Abualrob, 2019; Jafnihirda et al., 2023). Scientific literacy is a crucial competency necessary to address global challenges that necessitate critical, creative thinking, and the ability to solve problems rationally (Fuadi et al., 2020). These skills are not only necessary in academic environments but also in everyday life when individuals face real-life problems that require logical and data-driven thinking. Therefore, mastery of scientific literacy is a crucial foundation for creating a generation that can actively participate in the modern technological era (Zotou et al., 2020; Chang et al., 2023).

However, studies indicate that the level of scientific literacy among students in Indonesia remains relatively low compared to other countries. One cause is the teacher-centered learning process and the lack of direct

How to Cite:
Mahmud, A. P. M., Mursalin, M., Abdjul, T., Pikoli, M., Yusuf, M., & Odja, A. H. (2025). A Virtual Laboratory to Improve the Effectiveness of Interactive Learning Media on Science Process Skills and Science Literacy in the Competency Aspects of Dynamic Electricity. *Jurnal Penelitian Pendidikan IPA*, *11*(11), 1441–1450. https://doi.org/10.29303/jppipa.v11i11.13531

scientific experience for students (Suparya et al., 2022). Theoretical learning leads students to memorize concepts without understanding their application in everyday life (Firmadani, 2020). When learning does not involve exploration activities, students tend to struggle with connecting concepts to real-world phenomena, resulting in a shallow understanding. This condition also impacts students' low science process skills (SPS). In fact, SPS play a crucial role in developing scientific thinking skills such as observing, interpreting data, and drawing conclusions (Tunisa & Astriani, 2023). Good SPS allows students to actively engage in the investigation process, test hypotheses, and reason based on evidence. Low SPS indicate that learning has not fully trained students to carry out the stages of the scientific method independently (Sudibyo, 2019; Usman & Huda, 2021).

Therefore, learning innovations are needed that can simultaneously develop both abilities through exploratory activities based on scientific inquiry. One approach that can be used is the guided inquiry learning model, where the teacher acts as a facilitator, guiding students to discover concepts through an investigative process (Wardani & Rosdiana, 2022). This model places students at the center of learning activities by providing space for them to make observations, formulate questions, test hypotheses, and conclude. Thus, students not only receive information but also construct understanding independently. This model is believed to enhance critical thinking skills, problem-solving abilities, and foster the development of scientific concepts in a gradual and structured manner (Yusuf & Widyaningsih, 2020; Fatimah et al., 2020; Ikhsan et al., 2020).

On the other hand, the implementation of laboratory activities in schools is often hampered by limited tools, materials, and time, especially in schools with limited facilities. To overcome these limitations, digital technology can be utilized through interactive learning media based on virtual laboratories using PhET simulations, which can realistically simulate scientific experiments in a digital environment (Arya et al., 2024; Mashami et al., 2023; Rahim & Ali, 2025). Virtual laboratories offer a learning experience that mimics real experiments without the associated risks and costs. Through computer-based simulations, students can independently conduct dynamic electricity experiments by changing variables and observing the results directly. This process allows students to gain scientific experiences that are safer, more flexible, and can be repeated at any time. In addition, simulation media provide a more concrete visualization of abstract concepts, allowing students to understand the relationships between variables more easily (Alnagrat et al., 2022; Wang et al., 2025; Rahmawati & Atmojo, 2021).

Several studies also support the effectiveness of using virtual laboratories to develop higher-order thinking skills. Sapriadil et al. (2018) demonstrated that the use of virtual laboratories can optimize students' scientific communication and creative thinking skills in understanding electrical concepts. Aydin (2016) also confirmed that implementing virtual laboratories can significantly improve students' conceptual understanding and learning motivation. Another study by Riska et al. (2023) found that a guided inquiry learning model assisted by virtual laboratories can improve students' scientific literacy skills. Meanwhile, Daud et al. (2025) demonstrated that implementing interactive learning media based on virtual laboratories is efficacious in improving students' scientific literacy in science learning. These results indicate that using virtual laboratories, supported by PhET simulations and a guided inquiry approach, not only improves conceptual understanding but also develops scientific skills through exploratory activities that mimic real-life experiments.

Therefore, this research is expected to provide an alternative science learning solution that can improve students' scientific literacy and science process skills through the implementation of interactive learning media based on virtual laboratories, supported by PhET simulations, and a guided inquiry approach in the context of dynamic electricity.

Method

This study employed a quasi-experimental method with a pretest-posttest control group design. This design was chosen because students took a pretest before the treatment was administered, and then a posttest after the treatment was completed, to determine their learning outcomes. In the experimental and replication classes, the treatment involved implementing interactive learning media based on the Virtual Laboratory (PhET) with a guided inquiry approach, as the research flow chart illustrated in Figure 1.

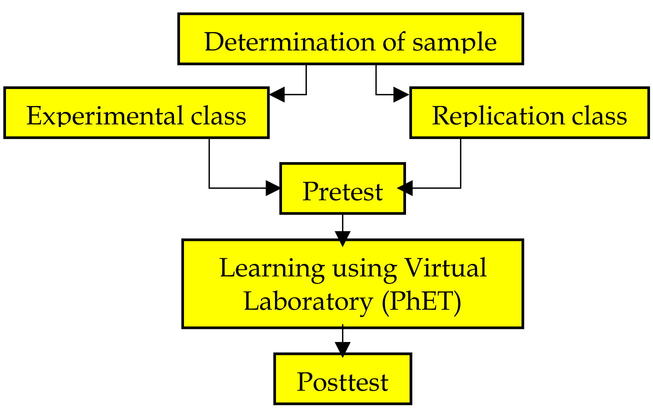

Figure 1. Research flow chart

This research was conducted in the odd semester of the 2025/2026 academic year at SMP Negeri 1 Kwandang and MTs Al-Khairaat Kwandang, North Gorontalo Regency, Gorontalo Province. The population consisted of all ninth-grade students from both schools. The sampling technique used was cluster sampling based on existing classes. The data were analyzed using normality tests, hypothesis tests, and the N-Gain test.

Results and discussion

This study aimed to examine the effectiveness of interactive learning media based on Virtual Laboratory (PhET) on students' science process skills (Skills) and scientific literacy. The study was conducted at SMP Negeri 1 Kwandang and MTs Al-Khairaat Kwandang. Data were obtained through Skills observation sheets during three meetings and a science literacy test (pretest–posttest) on dynamic electricity.

Science Process Skills Observation Results

Science process skills were measured using eight indicators: observing, classifying, asking questions, formulating hypotheses, designing experiments, conducting experiments, interpreting data, and drawing conclusions. Observations showed that all classes, both the experimental and replication classes, experienced improvement in each indicator from the first to the third meeting.

The indicators with the highest improvement were observing (I1) and conducting experiments (I6), demonstrating that the use of Virtual Laboratory (Skills) helped students make more thorough observations and carry out experimental procedures more independently and systematically. A visualization of the development of Skills of Student Learning Objectives (SLO) in each class is presented in Figures 2-5.

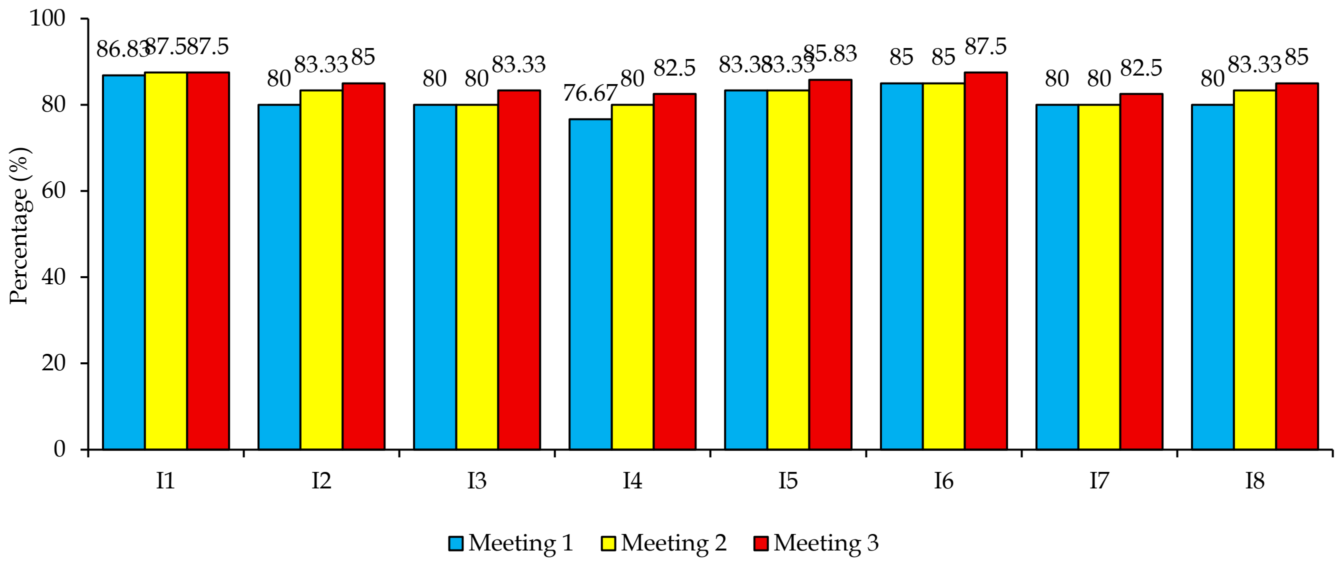

Figure 2. SLO improvement for experimental 1 of SMP Negeri 1 Kwandang

Based on Figure 2, improvements in experimental class 1 were found in the observing (I1) and conducting experiments (I6) indicators, indicating that the use of the Virtual Laboratory (PhET) significantly assisted students in understanding dynamic electrical phenomena visually and interactively. Simulations allow students to quickly change variables, such as current, voltage, and resistance, allowing them to observe changes directly and repeatedly. This makes the observation process more accurate and in-depth. These results align with research by Al-Nakhle (2022), which states that virtual laboratories improve students' scientific skills because they provide opportunities for exploration that are not limited by tools, time, or risk. With a flexible virtual environment, students can conduct experiments independently and review experimental steps without relying on a physical laboratory.

Furthermore, the improvement in experimental skills (I6) was supported by the implementation of the guided inquiry model used in the learning. According to Djola et al. (2021), the integration of guided inquiry and virtual simulations allows students to follow a more directed scientific workflow, from formulating problems to drawing conclusions based on experimental data. This approach makes students more active in conducting experiments and more systematic in collecting and analyzing data.

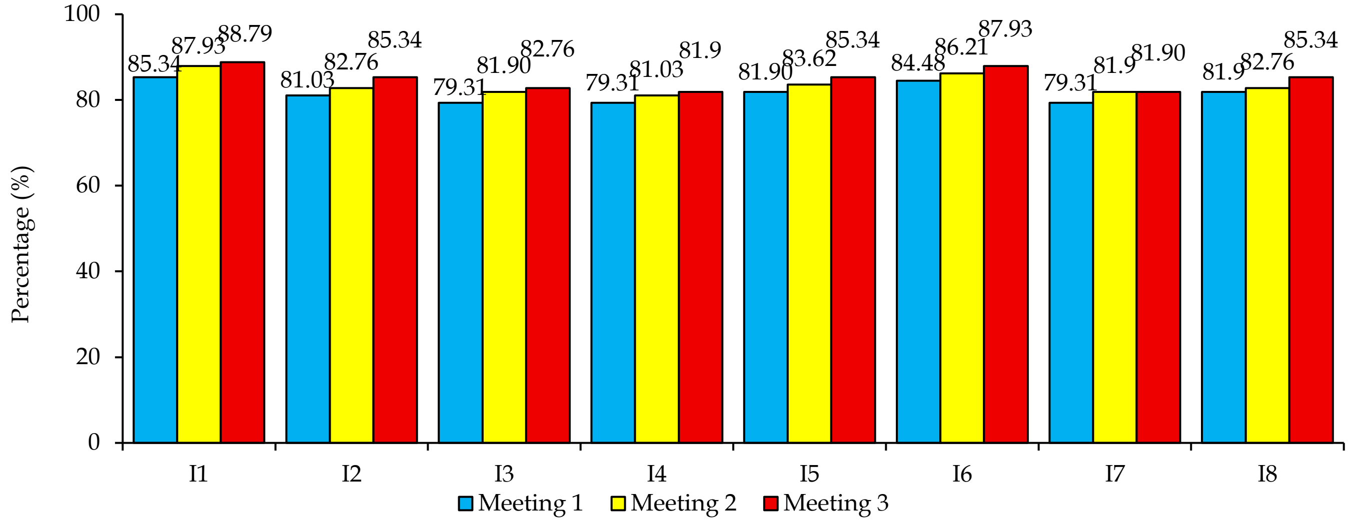

Figure 3. SLO improvement for experimental 2 of SMP Negeri 1 Kwandang

Based on Figure 3, the improvement in experimental class 2 reinforces the pattern found in experimental class 1, namely that learning using Virtual Laboratory (PhET) has a consistent positive impact on the development of SLO. The dominant improvement in the observing and conducting experiments indicators indicates that students are increasingly able to make directed observations and carry out experimental procedures more effectively.

This aligns with the research findings of Hartati et al. (2022), which state that interactive simulation media help students observe phenomena in detail and systematically, thereby strengthening their ability to understand concepts based on experimental results. PhET, which provides a visual representation of electrical circuits, enables students to observe relationships between variables that are difficult to discern through direct laboratory experiments. Furthermore, the improvement in the conducting experiments indicator (I6) also aligns with the findings of Daud et al. (2025), who explained that virtual laboratories allow students to conduct repeated experiments without limitations on tools and materials.

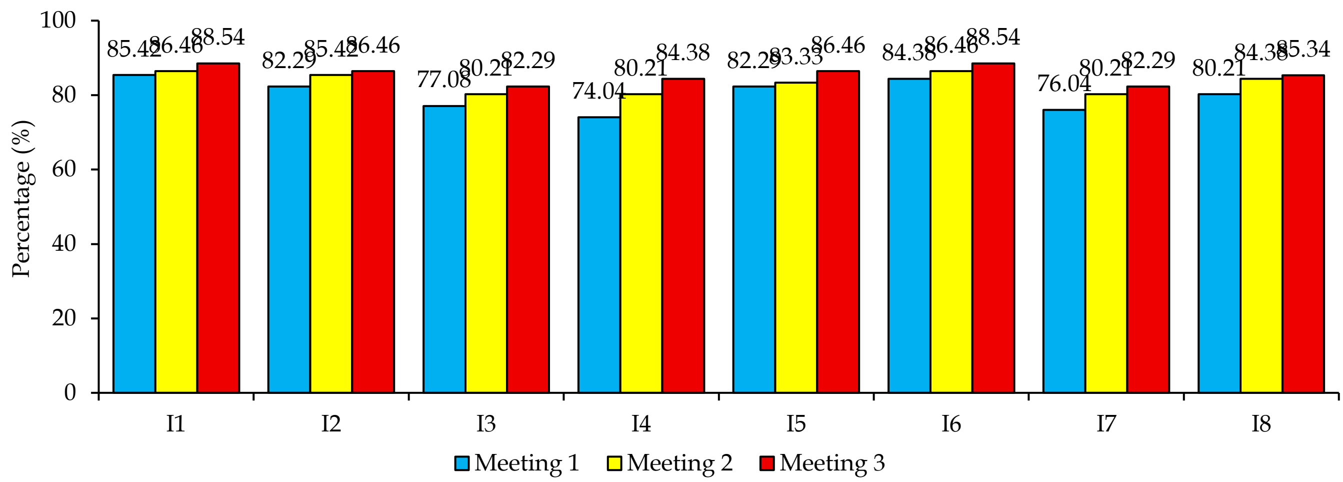

Figure 4. SLO improvement for replication 1 of MTs Al-Khairaat Kwandang

Based on Figure 4, the improvement in KPS in replication class 1 shows that all KPS indicators improved from the first to the third meeting. Observing (I1) and conducting experiments (I6) indicators again showed the most significant improvement. Scores increased in other indicators, such as classification, hypothesis formulation, and data interpretation, and were also relatively stable, although not as high as those of the two leading indicators.

This aligns with the findings of Al-Nakhle (2022), who emphasized that virtual simulations provide students with the opportunity to conduct unlimited observations and repeat experiments without risk or equipment constraints. The improvement in the conducting experiments indicator (I6) also demonstrates that students can follow scientific work procedures more independently. According to Tunisa & Astriani (2023), simulation-based practicum activities can improve students' procedural skills because they practice designing and conducting experiments repeatedly in a safe and flexible context.

Figure 5 shows that replication class 2 also experienced improvements in all science process skills indicators. Like the other classes, the highest improvements were seen in observation (I1) and conducting experiments (I6) indicators. Simulations enable students to explore electrical circuits through visual observation, significantly enhancing their observational skills. This finding supports the assertion of Hartati et al. (2022) assertion that exploratory experiences through virtual experiments help students grasp evidence-based scientific concepts more firmly.

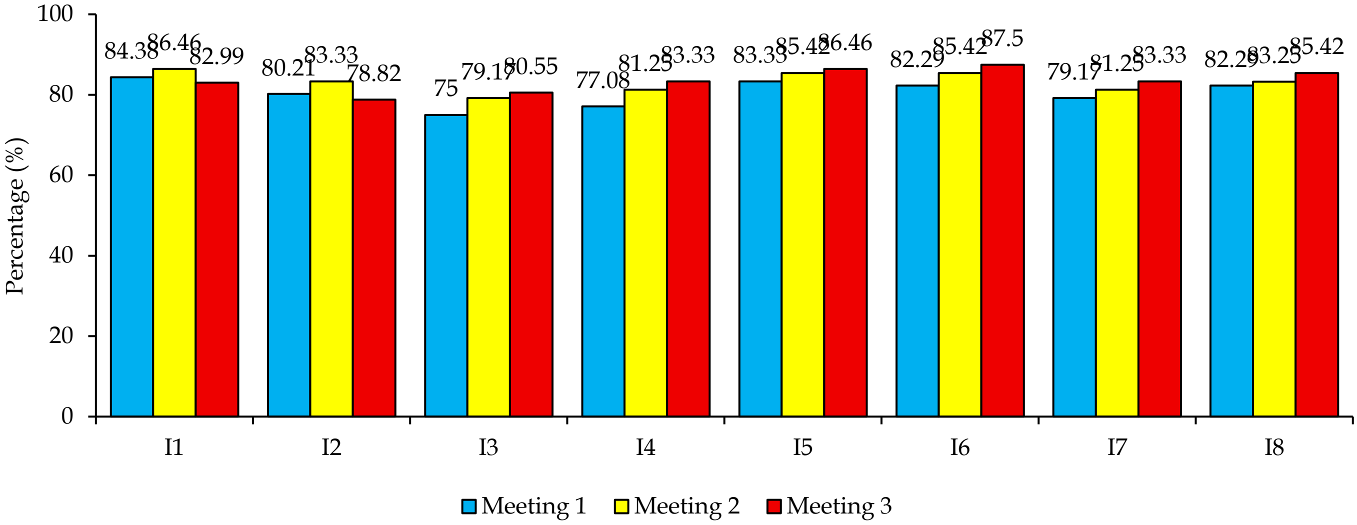

Figure 5. SLO improvement for replication 2 of MTs Al-Khairaat Kwandang

Scientific Literacy Results

Students' scientific literacy was measured using 10 essay questions structured around three PISA scientific literacy indicators: identifying scientific issues, explaining scientific phenomena, and using scientific evidence to support their claims. The tests were administered before and after learning using the Virtual Laboratory (PhET) media. The pretest–posttest results showed an increase in achievement across all indicators in each class, both the experimental and replication classes. To more clearly demonstrate the upward trend, the achievement of these three indicators is presented in Figures 6 and 7.

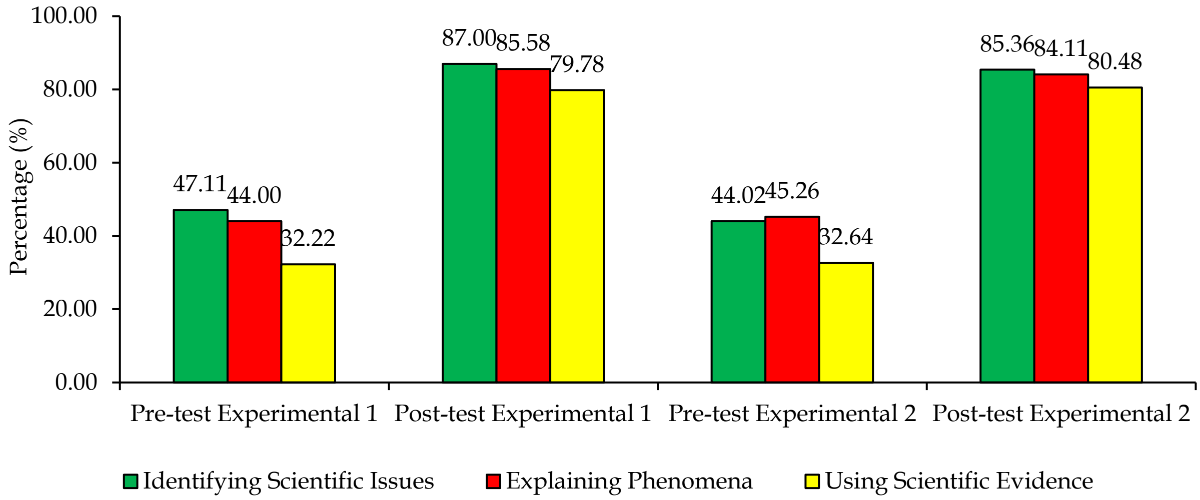

Figure 6. Pretest and posttest achievements of science literacy in the experimental class

Based on Figure 6, the improvement in scientific literacy in the experimental class indicates that the use of interactive learning media based on Virtual Laboratory (PhET) was effective in helping students understand the concept of dynamic electricity more deeply. Based on the pretest-posttest results, all scientific literacy indicators experienced significant improvement after the learning process. Identifying scientific issues was the indicator with the highest improvement, followed by explaining scientific phenomena and using scientific evidence. This pattern suggests that the PhET simulation facilitated students' understanding of the context of scientific problems and helped them analyze the relationships between electrical variables.

This improvement is supported by the findings of Mellyzar et al. (2022), who explained that interactive simulation-based learning can improve scientific literacy skills because students have the opportunity to explore scientific phenomena through easy-to-understand visualizations. With the current and voltage measurement features in PhET, students can make repeated observations and independently understand the relationships between electrical variables. Furthermore, the improvement in scientific literacy in the experimental class aligns with the findings of Karira & Sunarti (2022), who suggest that interactive media helps students construct scientific reasoning and explain phenomena.

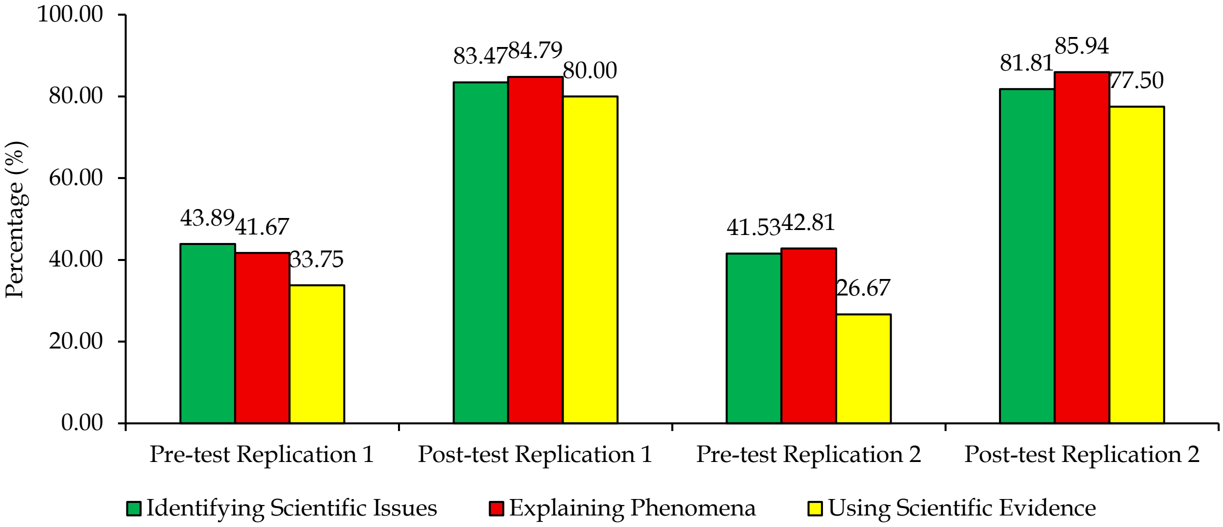

Figure 7. Pretest and posttest achievements of science literacy in the replication class

Based on Figure 7, the increase in scientific literacy in the replication class shows a consistent pattern across all indicators, with the largest increase in the indicator explaining scientific phenomena. This indicates that the use of Virtual Laboratory (PhET) helps students understand the relationships between dynamic electricity concepts more coherently. Visualizing changes in current, voltage, and resistance in real time makes it easier for students to connect cause and effect in a circuit, thus improving their ability to explain scientific phenomena. This finding aligns with Karira & Sunarti (2022) who stated that interactive simulations can strengthen students' ability to explain scientific processes systematically. Furthermore, exploration-based learning experiences through virtual labs provide opportunities for students to make repeated observations and build evidence-based understanding, as explained by Almira et al. (2023).

Improvements in other indicators, such as identifying scientific issues and using scientific evidence, also show positive developments. The use of PhET simulations allows students to independently observe electrical phenomena and relate them to everyday contexts, thus helping them recognize scientific problems more concretely. This aligns with Suparya et al. (2022), who emphasized that scientific literacy improves when students can connect concepts to real-life situations. Furthermore, the use of technology-based learning media also supports the strengthening of conceptual understanding and scientific thinking skills. This aligns with Abdjul et al. (2019), who stated that Virtual Laboratories can improve students' physics learning outcomes through digital experimental experiences.

Overall, the improvements in the experimental and replication classes suggest that Virtual Laboratory (PhET)-based learning is effective in enhancing students' scientific literacy. The consistency of findings across two schools with different characteristics indicates that virtual labs can be used adaptively to support science learning.

The classroom learning process involves interactions between teachers and students to support understanding of dynamic electricity concepts. To assess the extent to which learning activities are implemented according to the stages of the guided inquiry model, an analysis of the implementation of learning is conducted using observation sheets. The results of observations in grade IX of SMP Negeri 1 Kwandang and MTs Al-Khairaat Kwandang are presented in Figures 8 and 9.

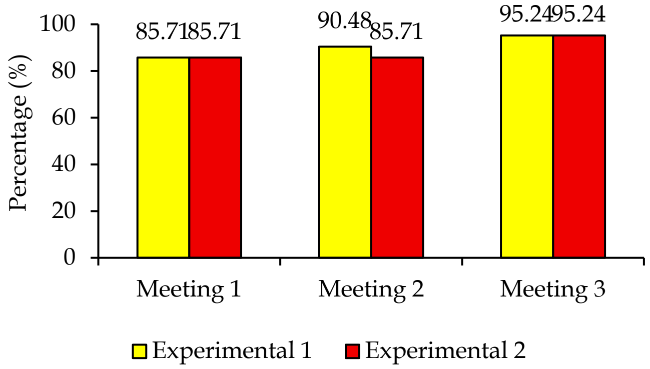

Figure 8. Implementation of learning in SMP Negeri 1 Kwandang

Based on Figure 8, the implementation of learning in Experimental Class 1 and Experimental Class 2 showed improvement from the first to the third meeting. This indicates that all stages of the guided inquiry model were implemented well and consistently according to the lesson plan. This aligns with the findings of Djola et al. (2021), who explained that the implementation of the guided inquiry model assisted by PhET simulations can increase student engagement and the effectiveness of classroom learning.

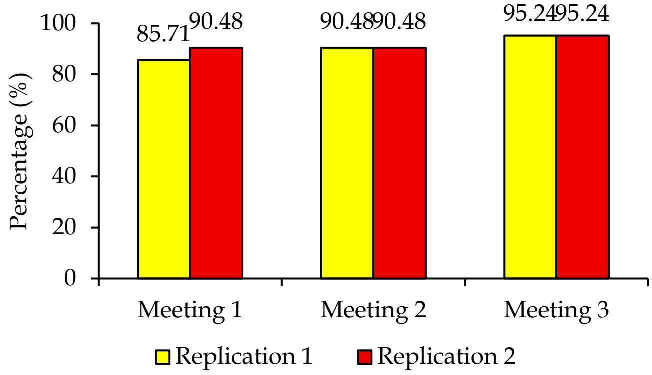

Figure 9. Implementation of learning in MTs Al-Khairaat Kwandang

Based on Figure 9, the implementation of learning in replication 1 and replication 2 classes showed improvement from the first to the third meeting. This indicates that all stages of the guided inquiry model were implemented consistently, as outlined in the lesson plan.

Normality Test

A normality test was conducted to assess whether student data was normally distributed. In this study, the normality test employed the Kolmogorov–Smirnov method, which was facilitated by Microsoft Excel. The test was conducted on student outcomes at SMP Negeri 1 Kwandang and MTs Al-Khairaat Kwandang after receiving Virtual Laboratory (PhET)-based learning, as presented in Table 1. Based on Table 1, the results of the data normality test indicate that Fi ≥ K for a significance level of $\alpha = 0.05$. Therefore, it can be concluded that the research data for the experimental and replication classes are normally distributed.

Table 1. Data normality test results

School	Class	Fi	K	Status
SMP Negeri 1 Kwandang	Experimental 1	0.48	0.26	Normal
	Experimental 2	0.48	0.25	Normal
MTs Al-Khairaat Kwandang	Replication 1	0.47	0.27	Normal
	Replication 2	0.47	0.27	Normal

Hypothesis Testing

Hypothesis testing was conducted using a paired sample t-test to determine whether there was a significant difference between students' pretest and posttest scores presented in Table 2. Based on Table 2, $T_{count} \geq T_{table}$ with a significance level of 0.05 for the experimental and replication classes. Therefore, H0 is rejected and Ha is accepted. This suggests that Virtual Laboratory-based learning is effective in enhancing students' understanding of dynamic electricity.

Table 2. Hypothesis testing results

School	Class	T_{count}	T_{table}	Status
SMP Negeri 1 Kwandang	Experimental 1	24.42	2.045	H_a accepted
	Experimental 2	21.47	2.048	H_a accepted
MTs Al-Khairaat Kwandang	Replication 1	20.83	2.069	H_a accepted
	Replication 2	23.78	2.069	H_a accepted

N-Gain Test

The n-gain test was conducted to measure the level of improvement in students' scientific literacy skills by comparing pretest and posttest scores. This analysis used Course Average Normalized Gain, and the results are presented in Table 3.

Table 3. N-Gain test results

School	Class	N-Gain	Criteria
SMP Negeri 1 Kwandang	Experimental 1	0.74	High
	Experimental 2	0.70	High
MTs Al-Khairaat Kwandang	Replication 1	0.72	High
	Replication 2	0.72	High

Based on Table 3, all classes showed a significant increase in scientific literacy skills after implementing Virtual Laboratory-based learning (PhET), with n-gain values in the high category. This confirms that this learning is efficacious in improving students' understanding of dynamic electricity. This finding aligns with the research results of Mellyzar et al. (2022), which demonstrated that interactive simulations can enhance students' scientific literacy by facilitating independent exploration of scientific phenomena. In addition, Almira et al. (2023) emphasized that the use of virtual laboratories provides students with opportunities to conduct repeated observations without risk, thereby strengthening their conceptual understanding and scientific thinking skills. Research by Daud et al. (2025) also supports the notion that Virtual Laboratory media are effective in facilitating investigation-based learning activities, improving data analysis skills, and fostering evidence-based reasoning in students.

Conclusion

Based on the research results, students' science process skills improved in all indicators, both in the experimental and replication classes, as evidenced by their ability to observe, classify, formulate hypotheses, interpret data, and draw conclusions. Overall, science process skills fell into the good to very good category, indicating that the Virtual Laboratory (PhET) encouraged students' active involvement in scientific activities. In addition, students' scientific literacy increased significantly, as indicated by the results of the paired t-test ($t_{count} \geq t_{table}$, $\alpha = 0.05$) and the high-category N-gain value. This confirms that the implementation of Virtual Laboratory (PhET)-based learning is efficacious in improving science process skills and science literacy, as well as creating interesting, contextual, and student-centered learning on dynamic electricity material.

Acknowledgments
Thanks are due to the Universitas Negeri Gorontalo and all colleagues who have supported the completion of this article.

Author Contributions
A.P.M.M.: conceptualization, writing-original draft preparation, methodology; M.: conceptualization, methodology; T.A.: curation, writing-original draft preparation, writing-review and editing; M.P.: methodology; M.Y.: formal analysis; A.H.O.: Validation.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

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