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Enhancing students' cognitive and science process skills through inquiry-based virtual experiments on electricity concepts

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Abstract. This study investigates the effectiveness of inquiry-based virtual experiments in improving elementary students' cognitive skills and science process skills in learning electricity concepts. The integration of digital simulations into elementary science instruction has become increasingly important for supporting conceptual understanding and scientific inquiry, particularly for abstract topics such as electricity. The population consisted of sixth-grade students at a public elementary school, from whom 25 were selected using purposive sampling based on technological readiness and curriculum alignment. The study employed a quasi-experimental design using a one-group pretest–posttest approach. The learning intervention was implemented through four inquiry-based sessions using PhET Interactive Simulations (Circuit Construction Kit: DC). Data were collected using two validated multiple-choice instruments: a 17-item cognitive test aligned with five levels of Bloom's Revised Taxonomy and an 18-item science process skills test measuring six indicators, including observing, classifying, predicting, interpreting data, drawing conclusions, and communicating. The instruments demonstrated good internal consistency (KR-21 = 0.83). Data were analyzed descriptively by comparing pretest and posttest scores. The results showed an increase in students' posttest mean scores, reaching 79.3% for cognitive skills and 73.1% for science process skills.

Introduction

Science, as an integral component of the elementary school curriculum, plays a vital role in establishing the foundations of students' scientific thinking, conceptual understanding, and science literacy from an early age (Al Sultan et al., 2021; Ploj Virtič, 2022). In the Indonesian educational context, science learning is expected to support two central dimensions: (1) the mastery of scientific concepts or cognitive abilities, and (2) the development of science process skills, which include observing, classifying, predicting, and designing as well as conducting simple investigations. These expectations are consistent with international perspectives, such as the PISA 2025 Science Framework (OECD, 2023), which emphasizes scientific reasoning, inquiry practices, and evidence-based thinking as essential competencies for learners in the 21st century.

One of the core science topics consistently introduced at various levels of elementary education is electricity. This topic is not only closely connected to students' daily experiences but also serves as a fundamental basis for understanding modern technological systems (Anam, 2021; Anam et al., 2025). However, it presents unique pedagogical challenges. Several studies have shown that elementary students often struggle to grasp concepts such as electric current, series and parallel circuits, and conductors and insulators because these ideas are abstract and cannot be observed directly. Despite its importance, electricity presents considerable pedagogical challenges. Previous studies have reported that elementary students often have difficulty understanding abstract concepts such as electric current, series and parallel circuits, and the properties of conductors and insulators. These difficulties are largely attributed to the abstract nature of electricity, which cannot be directly observed, as well as to students' stage of cognitive development. Most elementary students are in the concrete operational stage, requiring learning experiences that are highly visual, hands-on, and exploration-oriented to support meaningful understanding (Reyes et al., 2024; Reyes & Villanueva, 2024; Taşar & Heron, 2023).

Evidence from classroom practice indicates that science instruction in elementary schools remains predominantly teacher-centered, relying heavily on lectures and textbook-based assignments, with limited opportunities for scientific exploration and experimentation (Reyes et al., 2024). Post-pandemic studies have revealed that teachers face numerous obstacles in conducting hands-on experiments, including limited equipment and materials, time constraints, and a lack of training in designing safe and effective laboratory activities (Siegel et al., 2022). Consequently, science learning is often reduced to verbal explanations and memorization, preventing students from engaging in authentic scientific processes and leading them to perceive science as a content-heavy subject rather than an investigative discipline (Sengul, 2024).

Consistent with these findings, preliminary data from classroom assessments in the study context indicate that approximately 70% of students answered correctly only at the lower cognitive levels of Bloom's Revised Taxonomy, namely remembering (C1) and understanding (C2). However, the percentage of correct responses declined substantially at higher-order cognitive levels (C3–C5), where only about 15% of students answered correctly. In addition, students' science process skills were found to be insufficiently developed, particularly in posing questions, classifying, predicting, planning investigations, drawing conclusions, and applying scientific concepts. These findings highlight the need for instructional approaches that provide students with opportunities to actively engage in scientific inquiry and conceptual exploration.

In response to these challenges, inquiry-based learning has gained attention as a student-centered pedagogical approach that actively engages learners in constructing knowledge. Through inquiry-based learning, students are encouraged to formulate questions, develop hypotheses, conduct investigations, analyze data, and draw conclusions based on empirical evidence (Kotsis, 2024; Evi Yupani & Widana, 2023; Mahsup et al., 2026). Research has shown that this approach is effective not only in improving students' conceptual understanding but also in fostering science process skills essential to scientific reasoning and problem-solving (Anam et al., 2025).

However, implementing inquiry-based learning through real laboratory experiments in elementary schools continues to be constrained by practical limitations. As an alternative, virtual experiments supported by interactive simulations, such as PhET Interactive Simulations, offer a promising solution (Maharani et al., 2024). These simulations enable students to explore electricity concepts in a visual, interactive, and safe virtual environment, allowing repeated experimentation and variable manipulation without the limitations of physical laboratories. Empirical studies have demonstrated that integrating PhET simulations with an inquiry-based approach can enhance students' conceptual understanding, engagement in learning, science process skills, and overall scientific thinking (Anam et al., 2025; Banda & Nzabahimana, 2021; Baran et al., 2020; I Made Elia Cahaya et al., 2024).

Moreover, inquiry-based virtual experiments have been shown to support the development of students' cognitive abilities across multiple levels of the Revised Bloom's Taxonomy, from lower-order skills such as remembering and understanding to higher-order skills including applying, analyzing, and evaluating. At the same time, this approach provides meaningful opportunities for students to develop science process skills, such as classifying information, designing investigations, making predictions, and relating scientific concepts to everyday phenomena (Anam et al., 2025; Yani & Widiyatmoko, 2023; Purnadewi & Widana, 2023).

Despite these promising findings, most existing studies on inquiry-based virtual experiments have focused on secondary or higher education contexts. There remains limited empirical evidence examining their effectiveness at the elementary school level, particularly in the learning of electricity concepts. This indicates a clear research gap in understanding how inquiry-based virtual experimentation simultaneously influences elementary students' cognitive abilities and science process skills. Based on this background, the present study seeks to address the following research question: (1) How does inquiry-based virtual experimentation affect elementary students' cognitive achievement in learning electricity concepts? (2) How does inquiry-based virtual experimentation improve elementary students' science process skills in learning electricity concepts? The objectives of this study are to measure the extent of improvement in elementary students' cognitive achievement across five levels of Bloom's revised taxonomy and to evaluate the enhancement of students' science process skills following the implementation of inquiry-based virtual experimentation in electricity learning, as indicated by the N-gain scores and their corresponding categories.

This study advances existing research by explicitly integrating inquiry-based virtual experimentation with a dual-outcome assessment framework that simultaneously measures five hierarchical levels of cognitive achievement (Bloom's revised taxonomy) and six distinct science process skill components in elementary electricity learning, an area in which prior studies have typically examined either conceptual understanding or process skills in isolation rather than within a unified experimental design.

Method

This study employed a quasi-experimental one-group pretest–posttest design to examine the effectiveness of inquiry-based virtual experiments in enhancing elementary students' cognitive abilities and science process skills in the domain of electricity. This design was chosen because the research context did not allow the use of a control group, yet it still enabled measurable assessment of changes in students' learning outcomes.

Participants and Sampling Techniques

The subjects of this study were 25 sixth-grade students from a public elementary school located in an urban area of Bandung, Indonesia. The participants were selected through purposive sampling to ensure they were suitable for the study's objectives and implementation. The selection criteria included the availability of adequate technological facilities, such as computers or tablets, and reliable internet access, which were necessary for conducting inquiry-based virtual experiments. In addition, students' basic digital literacy and readiness to engage in simulation-based learning were considered to minimize potential technological barriers during the learning process.

This research was conducted during the second semester of the 2024/2025 academic year as part of regular science instruction on electricity concepts. The research activities were carried out over approximately 4 weeks, including the preparation stage, the implementation of the learning intervention, and the final evaluation stage. The selected school implemented a curriculum that was aligned with the electricity concepts addressed in this study, including electrical circuits, conductors and insulators, and the safe use of electrical energy. The learning intervention was implemented during regular science lessons, ensuring integration with the existing instructional schedule. All participants participated in the same learning activities and assessments, enabling consistent data collection. This approach ensured that the study was conducted in an authentic classroom setting while maintaining methodological rigor and ethical considerations.

The research involved the classroom teacher and the researcher. The classroom teacher facilitated the learning activities and maintained the regular classroom environment, while the researcher designed the intervention, administered the research instruments, and conducted the data analysis. This approach ensured that the study was conducted in an authentic classroom setting while maintaining methodological rigor and ethical considerations. However, it is important to acknowledge that the relatively small sample size and the use of a one-group pretest–posttest design may limit the generalizability of the findings. Therefore, the results of this study should be interpreted within the specific context of the participating school and are intended primarily to provide preliminary evidence regarding the effectiveness of inquiry-based virtual experiments in elementary science learning.

Learning Intervention

The learning intervention was implemented over four structured sessions using a scientific inquiry approach. Each session guided students through key inquiry stages, including orientation, formulating research questions, designing simple investigations, conducting virtual experiments, analyzing the obtained data, and drawing conclusions. This structured sequence was intended to engage students in the learning process actively and to support the development of both conceptual understanding and science process skills related to electricity.

All stages of the inquiry process were supported by PhET Interactive Simulations, particularly the Circuit Construction Kit: DC module. This simulation enabled students to construct and modify electrical circuits, observe the effects of changes in circuit components, and test their predictions in real time within a safe virtual environment. The use of interactive simulations facilitated the visualization of abstract concepts and provided students with hands-on learning experiences that would be difficult to achieve through conventional classroom experiments alone.

Research Instruments

Two research instruments were developed and used in this study to assess students' Cognitive Ability and Science Process Skills (SPS) in the context of learning about electricity. Both instruments were designed to align with the learning objectives of the inquiry-based virtual experiment intervention and to ensure valid and reliable measurement of students' learning outcomes:

Cognitive Ability Test

The Cognitive Ability Test consisted of 17 multiple-choice items developed based on the Revised Bloom's Taxonomy. The test covered five cognitive levels, namely remembering (C1), understanding (C2), applying (C3), analyzing (C4), and evaluating (C5), to capture students' cognitive performance from lower- to higher-order thinking skills. The items were constructed in accordance with the electricity content taught during the intervention. They were reviewed by subject-matter and assessment experts to ensure content validity, clarity, and alignment with the intended cognitive levels. Prior to implementation, the instrument underwent a field trial to assess its psychometric properties.

Item analysis from the trial indicated that the difficulty indices ranged from 0.32 to 0.71, representing moderate item difficulty, while the discrimination indices ranged from 0.31 to 0.64, indicating acceptable to good discriminant power. The results also indicated a high level of internal consistency, with a KR-21 reliability coefficient of 0.83, demonstrating that the test was suitable for measuring students' cognitive learning outcomes. The results indicated a high level of internal consistency, with a KR-21 reliability coefficient of 0.83, demonstrating that the test was suitable for measuring students' cognitive learning outcomes.

Science Process Skills (SPS) Test

The SPS Test comprised 18 multiple-choice items designed to measure six key indicators of science process skills: posing questions, classifying, predicting, planning investigations, drawing conclusions, and applying scientific concepts. These indicators reflect essential skills emphasized in inquiry-based science learning and were directly integrated into the virtual experiment activities. Similar to the cognitive test, the SPS instrument underwent expert validation to ensure each item is relevant and representative of the targeted skills.

Results from the empirical item analysis showed that the difficulty indices ranged from 0.35 to 0.69 and the discrimination indices ranged from 0.30 to 0.61, indicating that the items were capable of differentiating students with varying levels of science process skills. An empirical trial was also conducted to evaluate the instrument's reliability, yielding a high reliability coefficient (KR-21 = 0.83). This indicates that the SPS test consistently measured students' science process skills and was appropriate for use in this study.

Research Procedure

The research procedure was organized into three interconnected stages: preparation, implementation, and the final stage. Each stage was systematically planned to ensure the rigor of the research process and the credibility of the findings, while maintaining consistency between the research objectives, intervention design, and data analysis.

Preparation Stage

During the preparation stage, the researchers established the study's foundational components. This stage involved developing two research instruments: the cognitive ability test and the science process skills (SPS) test, based on indicators derived from the Revised Bloom's Taxonomy and commonly accepted SPS indicators in the science education literature. To ensure content validity and alignment with the targeted competencies, the instruments were reviewed by experts, including science education lecturers and experienced elementary school teachers. Furthermore, a field trial was conducted in a school with characteristics similar to those of the research site. Data from this trial were used to examine item reliability, difficulty levels, and discriminating power, which informed the revision and finalization of the instruments prior to their use in the main study.

Implementation Stage

The implementation stage constituted the core of the research and involved the execution of the learning intervention. At the beginning of this stage, a pretest was administered to all participants to determine their initial levels of cognitive ability and science process skills. The inquiry-based virtual experiment lessons were then conducted over several structured sessions using PhET interactive simulations. These sessions followed the main phases of scientific inquiry, including orientation, question formulation, planning investigations, conducting virtual experiments, analyzing results, and drawing conclusions. Throughout implementation, the learning process was monitored using a structured observation sheet completed by both the researcher and a collaborating teacher to ensure activities were carried out in accordance with the designed learning scenarios. After the intervention, a posttest was administered to assess changes in students' cognitive abilities and SPS.

Final Stage
In the final stage, the focus shifted to data processing and analysis. Pretest and posttest scores were analyzed using descriptive quantitative techniques, including the calculation of mean scores and Normalized Gain (N-Gain) values for each measured aspect. The results were then interpreted to evaluate the effectiveness of the inquiry-based virtual experiment in improving students' learning outcomes. Based on these analyses, conclusions were drawn to reflect the extent to which the intervention contributed to the development of students' cognitive abilities and science process skills, supported by empirical evidence from the study.

Data Analysis Techniques
Data from the pretest and posttest were analyzed using descriptive quantitative methods to examine changes in students' cognitive abilities and science process skills after participating in an inquiry-based virtual experiment on electricity concepts. Students' responses on both the cognitive ability test and the SPS test were scored dichotomously: each correct answer received a score of 1, and each incorrect answer received a score of 0. The total score for each student was then converted into a percentage to allow for uniform comparison across tests using the following formula:

$$\text{Score} = (\text{Obtained Score} / \text{Maximum Score}) \times 100 \qquad (1)$$

This scoring procedure provided a clear representation of students' achievement levels before and after the intervention.

To determine the magnitude of students' learning improvement, the Normalized Gain (N-Gain) was calculated by comparing pretest and posttest scores using the formula N-Gain:

$$\text{N-Gain} = (\text{Posttest} - \text{Pretest}) / (\text{Maximum Score} - \text{Pretest}) \qquad (2)$$

T The N-Gain values were interpreted using the criteria proposed by Hake (1998, 1999), as shown in Table 1.

Table 1. N-Gain Score Category

Score Range	Category
N-Gain ≥ 0.7	High
0.3 ≤ N-Gain < 0.7	Medium
N-Gain < 0.3	Low

These categories were used to evaluate the learning model's effectiveness at both the individual and class-average levels. In addition, N-Gain analysis was conducted for each cognitive domain (C1–C5) and each SPS indicator to identify the specific aspects that demonstrated the most significant improvement as a result of the intervention.

In addition to quantitative data, the study included observations of the lesson implementation to evaluate the extent to which the inquiry-based simulation model was conducted as planned. Observation data were analyzed descriptively using percentages of observed learning activities, calculated as follows.

$$\text{Implementation (\%)} = (\text{Number of Observed Activities} / \text{Total Planned Activities}) \times 100 \qquad (3)$$

The resulting percentages were interpreted using predefined implementation criteria to determine the level of consistency between planned and actual instruction. These observation findings served as triangulation data to support and strengthen the interpretation of students' learning outcomes, the researchers used the criteria in Table 2.

Table 2. Implementation of the Inquiry Learning Model

Implementation Percentage (%)	Criteria
0	No activity implemented
0 - 25	A small portion of activities implemented
26 - 49	Nearly half of the activities implemented
51 - 75	Half of the activities implemented
76 - 99	Most activities implemented
100	Almost all activities are implemented

Results and Discussion

This study investigated the effectiveness of inquiry-based virtual experiments supported by PhET Interactive Simulations in improving elementary students' cognitive abilities and science process skills (SPS) on electricity concepts. The learning intervention was implemented in a virtual classroom setting, emphasizing active student engagement through structured inquiry stages. The results presented focus on students' cognitive learning outcomes as measured by pretest and posttest scores.

Improvement in Cognitive Abilities

The pretest results indicated that students' average cognitive ability prior to the intervention was 61.4%, which falls within the medium category. This result suggests that, although students possessed a basic understanding of electricity concepts, their comprehension and higher-order thinking skills had not yet developed optimally. After participating in the inquiry-based virtual experiment learning activities, students' average posttest score increased to 79.3%. The calculated N-Gain value of 0.46 places this improvement in the moderate category, indicating a meaningful enhancement in students' cognitive performance following the intervention.

As illustrated in Image 1, the increase in average scores demonstrates that inquiry-based learning supported by interactive simulations can effectively facilitate students' conceptual understanding, even when conducted in a virtual learning environment. The visual and interactive features of the PhET simulations appear to help students explore abstract concepts of electricity more concretely, enabling them to test ideas, observe outcomes, and revise their understanding through inquiry processes. These findings suggest that virtual experiments, when designed and implemented systematically, can serve as an effective alternative to traditional hands-on experiments in elementary science learning.

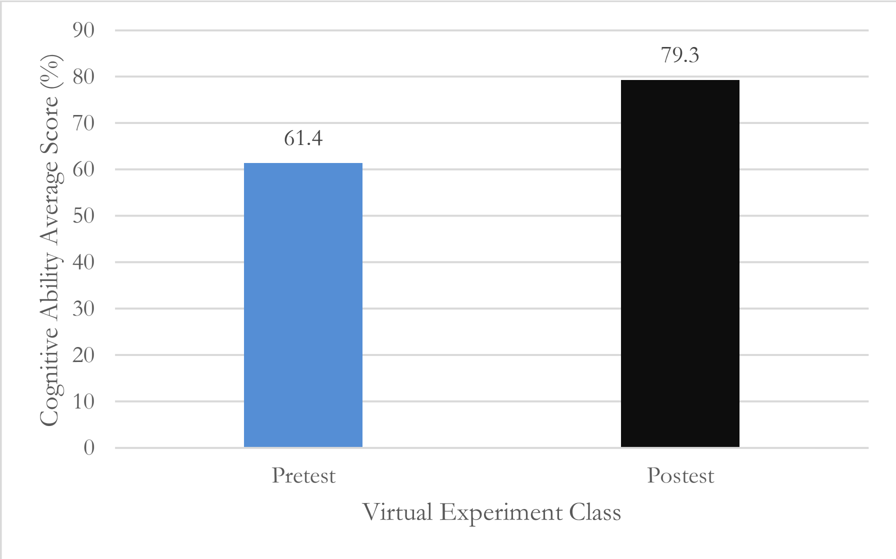

Image 1. Pretest and Posttest Scores of Students' Cognitive Abilities

Analysis of Cognitive Domain

An analysis was conducted based on the Revised Bloom's Taxonomy to examine the depth of improvement across different levels of thinking. The results are shown in Table 3.

Table 3. Analysis of Cognitive Domains

Cognitive Domain	Pretest (%)	Posttest (%)	N-Gain	Category
C1 – Remembering	70.67	96.00	0.86	High
C2 – Understanding	68.00	90.67	0.71	High
C3 – Applying	60.00	68.00	0.20	Low
C4 – Analyzing	54.67	82.00	0.60	Medium
C5 – Evaluating	44.00	62.67	0.33	Medium

To further examine the nature of students' cognitive development, an analysis was conducted across the five cognitive domains of the Revised Bloom's Taxonomy (C1–C5), as presented in Table 3. The results reveal that the greatest improvements were observed in the lower cognitive domains, particularly C1 (remembering) and C2 (understanding), with N-Gain values of 0.86 and 0.71, respectively, both categorized as high. This indicates that the inquiry-based virtual experiments were highly effective in strengthening students' factual recall and conceptual understanding of electricity concepts.

Moderate improvements were identified in the higher-order cognitive domains of C4 (analyzing) and C5 (evaluating), with N-Gain values of 0.60 and 0.33, respectively. These findings suggest that the inquiry activities supported students in interpreting data, identifying relationships within electrical circuits, and making basic judgments based on experimental results. However, the improvement in C3 (applying) was relatively low, with an N-Gain of 0.20. This result indicates that students experienced greater difficulty in transferring learned concepts to new or slightly varied problem situations.

The lower gain in the applying domain may imply that students require more extensive practice, real-world contextual problems, or additional instructional scaffolding to strengthen their ability to apply electricity concepts effectively. Overall, the distribution of N-Gain scores across cognitive domains indicates that inquiry-based virtual experiments are efficient for developing foundational and conceptual knowledge. At the same time, higher-level application skills may need reinforcement through complementary learning strategies.

Science learning through inquiry-based virtual experiments demonstrated a meaningful impact on improving students' cognitive abilities, consistent with previous findings in science education research (Yani & Widiyatmoko, 2023). The use of interactive simulations enabled students to develop a clearer understanding of fundamental electricity concepts by presenting abstract phenomena in a visual, dynamic manner. Rather than relying solely on verbal explanations or textbook descriptions, students were able to directly observe the flow of electric current, the relationships among circuit components, and the effects of manipulating variables within a system, thereby supporting conceptual clarity (Anam et al., 2025).

The learning process was structured around inquiry stages, including observation, questioning, experimentation, and drawing conclusions, which encouraged students to actively construct knowledge and engage in scientific thinking (Kranz et al., 2023; Setiawan & Sugiyanto, 2020). This approach effectively supported the development of lower-order cognitive skills, particularly remembering and understanding, which serve as essential foundations for more advanced learning in science (Kaneza et al., 2024). The substantial gains observed in these domains indicate that inquiry-based virtual experiments are well-suited for strengthening students' basic conceptual and factual knowledge.

Despite these positive outcomes, the findings also indicate that students continued to experience difficulties when applying learned concepts to new or contextualized problem situations. This suggests that while simulation-based learning is effective in reinforcing declarative and procedural knowledge, it may be less sufficient in promoting conceptual transfer and problem-solving without additional instructional support (Anam et al., 2025; Yani & Widiyatmoko, 2023). Similarly, higher-order cognitive processes, such as evaluating alternative solutions, interpreting data critically, and constructing well-reasoned arguments, were not fully optimized through virtual experiments alone (Matovu et al., 2023; Papalazarou et al., 2024; Wahyudi et al., 2024).

These results highlight the importance of complementary pedagogical strategies to enhance students' reflective and metacognitive abilities. Integrating guided reflection, structured discussions, and analytical tasks alongside simulation activities may help students deepen their reasoning and engage more critically with scientific concepts (Anam et al., 2025; Yani & Widiyatmoko, 2023).

Overall, inquiry-based virtual experiments have proven to be effective tools for helping students develop independent conceptual understanding, particularly for abstract science topics such as electricity (Gnesdilow & Puntambekar, 2025; Papalazarou et al., 2024; Reyes et al., 2024; Tisoglu et al., 2025). However, success in cultivating higher-order thinking depends largely on the pedagogical design that encourages deeper, more active student engagement.

Improvement in Science Process Skills (SPS)

The results of the science process skills (SPS) assessment indicate a substantial improvement in students' scientific skills following participation in the inquiry-based virtual experiment learning activities. Prior to the intervention, students achieved an average pretest score of 39.6%, which reflects a relatively low initial level of science process skills. After implementing inquiry-based learning supported by PhET simulations, the average posttest score increased markedly to 73.1%. The resulting N-Gain value of 0.52 falls within the medium category, indicating a meaningful improvement in students' SPS following the learning intervention.

As illustrated in Image 2, the considerable increase between pretest and posttest scores suggests that inquiry-based learning in a virtual environment can effectively promote the development of essential scientific skills. Through interactive simulations, students were actively involved in observing phenomena, manipulating variables, and interpreting outcomes, which are core components of science process skills. These findings demonstrate that, despite the absence of physical laboratory activities, well-designed virtual experiments can support students' active engagement and independent scientific thinking.

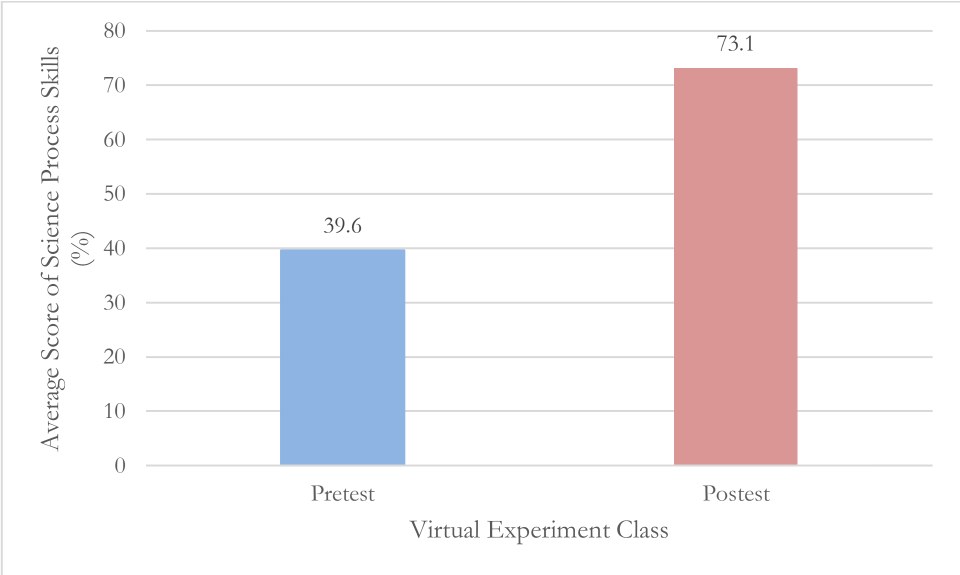

Image 2. Improvement in Science Process Skills (SPS) from Pretest to Posttest

Analysis of Science Process Skills

An analysis was conducted based on science process skills indicators to examine the extent of improvement across different dimensions of students' scientific skills. The results of this analysis are presented in Table 4.

Table 4. Analysis of SPS Indicators

SPS Indicator	Pretest (%)	Posttest (%)	N-Gain	Category
Asking Questions	34.67	68.00	0.51	Medium
Classifying	45.33	80.00	0.63	Medium
Predicting	46.67	85.33	0.72	High
Planning Investigations	34.00	68.00	0.52	Medium
Drawing Conclusions	42.00	72.00	0.52	Medium

As presented in Table 4. The results show that all assessed indicators improved in the medium-to-high categories, indicating a consistent positive impact of the inquiry-based virtual experiment across different dimensions of SPS. Among the indicators, predicting showed the greatest improvement, with an N-Gain value of 0.72, categorized as high. This finding suggests that simulation-based learning effectively supports students in formulating predictions based on observed patterns and experimental evidence, as the PhET simulations allow students to test hypotheses and immediately observe the consequences of their predictions.

Moderate improvements were observed in classifying, planning investigations, and drawing conclusions, each with N-Gain values in the medium category. These results indicate that students were able to organize information, design simple investigative procedures, and derive conclusions from virtual experimental data with increasing proficiency. In contrast, asking questions showed the least improvement, though it still fell within the medium category. This suggests that while inquiry-based simulations encourage active exploration, students may require more explicit guidance, structured prompts, or teacher modeling to develop higher-quality scientific questions. Overall, the indicator-based analysis confirms that inquiry-based virtual experiments are particularly effective in strengthening predictive and analytical aspects of science process skills, while reflective and exploratory questioning skills may benefit from additional instructional scaffolding.

With respect to science process skills, the results indicate that inquiry-based virtual experiments also contributed positively to students' development of these skills. Through systematic exploratory activities, students were supported in engaging with key scientific practices, such as designing simple investigations, making predictions, observing outcomes, and drawing conclusions (Chen et al., 2024; Widana et al., 2020). They were guided to design simple experiments, observe changes, make predictions, and draw conclusions independently. These activities align with the core philosophy of science learning, which emphasizes the process rather than just the outcome (Anam, 2020; Juniantari et al., 2025).

Virtual simulations provided learning experiences that closely approximated real laboratory activities while overcoming typical constraints related to safety, time, and equipment availability (Matovu et al., 2023; Papalazarou et al., 2024; Wahyudi et al., 2024). Students were able to repeat experiments, explore multiple scenarios, and observe cause-and-effect relationships in a controlled environment. As a result, skills such as planning investigations, classifying information, and interpreting experimental results showed notable improvement, aligning with findings from prior studies on simulation-based inquiry learning (Chen et al., 2024; Tsivitanidou et al., 2021).

However, the ability to independently formulate scientific questions remained relatively less developed. Although students demonstrated active engagement during exploration, many were not yet accustomed to generating investigable questions independently (Herranen & Aksela, 2019). This suggests that questioning skills require explicit instructional scaffolding rather than emerging solely from exploratory activities. Providing guiding questions, structured prompts, or reflective worksheets may help students develop stronger inquiry-oriented questioning skills.

Additionally, the application of scientific concepts to real-life contexts was not fully optimized. While students were generally able to follow and replicate simulation procedures, they required further guidance to connect experimental findings with everyday phenomena (Al-nakhle, 2022). Strengthening this connection through contextual discussions, real-world examples, or case-based learning may enhance the relevance and transferability of knowledge gained through simulations (Al-nakhle, 2022; Shen et al., 2024; Simanjuntak et al., 2021).

In conclusion, inquiry-based virtual experiments demonstrate strong potential to develop students' foundational scientific thinking, particularly by promoting active engagement and supporting self-directed learning. The effectiveness of this approach lies in its ability to combine interactive simulations with structured inquiry activities that guide students to explore phenomena, test ideas, and construct understanding independently. Nevertheless, the optimal development of science process skills depends not only on the use of technology but also on the deliberate integration of well-designed simulations, systematic exploration phases, and reflective pedagogical strategies that help students connect experimental experiences with scientific concepts and reasoning.

Implementation of the Inquiry Learning Model

Based on the implementation rubric, the results of this study indicate that the inquiry-based learning model supported by virtual experiments was implemented at a very high level in the experimental class. The observation data show that Learning Session 1 on electrical conductors and insulators achieved a 100% implementation rate, meeting the criterion "almost all activities implemented." This result indicates that all planned inquiry learning activities—ranging from orientation and question formulation to virtual experimentation and conclusion drawing—were carried out entirely in accordance with the lesson plan.

Similarly, Learning Session 2 on electrical circuits achieved a 100% implementation rate, meeting the same criterion. This finding suggests that the inquiry-based virtual experiment model was consistently and effectively implemented across different electricity topics. The complete implementation reflects strong alignment between the designed instructional scenarios and actual classroom practice, as well as effective collaboration between the teacher and students during the learning process.

Overall, these results demonstrate that the inquiry-based learning model using virtual experiments was implemented optimally in the experimental class. The high level of implementation supports the validity of the research findings, as improvements in students' cognitive abilities and science process skills can be attributed to a well-executed instructional intervention.

Research Limitations

Although this study provides preliminary evidence on the effectiveness of inquiry-based virtual experiments in enhancing elementary students' cognitive and science process skills, several limitations should be acknowledged. First, the use of a one-group pretest–posttest design without a control group restricts the ability to attribute observed learning gains solely to the intervention, as other external factors may have influenced the outcomes. Second, the relatively small sample size (n = 25) and the single-school context limit the generalizability of the findings to other elementary schools with different characteristics. Finally, although the instruments were validated and reliable, the study relies primarily on quantitative measures, which may not fully capture students' depth of engagement or conceptual understanding. Future research could address these limitations by incorporating control groups, larger and more diverse samples, and complementary qualitative methods.

Educational Implications

The findings of this study have important implications for elementary science teaching. This study is novel in integrating inquiry-based virtual experiments with a dual assessment framework that measures both cognitive and science-process skills in elementary electricity learning. Integrating interactive simulations into electricity lessons can effectively support the development of both cognitive skills and science process skills. Teachers can use interactive simulations to provide students with opportunities to engage in authentic scientific inquiry, especially in contexts where resources, time, or safety concerns limit hands-on experiments. Furthermore, emphasizing structured inquiry and guided experimentation can help students move beyond rote memorization, fostering higher-order thinking and a deeper understanding of scientific concepts. These insights can guide curriculum planning and instructional strategies, encouraging the adoption of technology-enhanced inquiry approaches in elementary science education.

Conclusion

The findings of this study demonstrate that inquiry-based virtual experiments supported by PhET simulations are effective in enhancing elementary students' cognitive abilities and science process skills in the topic of electricity. Students are actively engaged in exploring phenomena, manipulating variables, observing outcomes, and drawing evidence-based conclusions, which confirms the effectiveness of the intervention in achieving the research objectives. The study also highlights that while students show significant improvement in understanding core concepts and developing science process skills, additional support is needed to enhance their ability to apply knowledge in unfamiliar contexts and to formulate investigable scientific questions. Based on these findings, it is recommended that elementary science teachers adopt inquiry-based virtual experiments in their lessons, integrating guided reflection, structured questioning, and interactive simulations to promote deeper conceptual understanding, higher-order thinking, and authentic engagement in scientific inquiry.

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