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Improving Scientific Explanation Competency in Elementary Students through Simulation-transformed Inquiry Learning Cycle on Electrical Circuits

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Abstract

Developing learners' competency in constructing scientific explanations is essential for fostering science literacy. 5E inquiry learning cycle enriched with interactive science simulations offers a promising strategy to actively engage students, support evidence-based reasoning, and build a solid scientific explanation competency vital for informed citizenship in the digital age. This study examines the impact of a simulation-infused inquiry learning cycle on sixth-grade students' scientific explanation competency about electrical circuits. A quasi-experimental design involved 77 students divided into experimental (n = 38) and control (n = 39) groups. The experimental group engaged with a simulation-transformed 5E inquiry learning cycle, while the control group received conventional 5E inquiry learning cycle. Pre- and post-test data were analyzed using SPSS. The results revealed that both groups improved significantly from pre-test to post-test. However, the experimental group showed significantly higher post-test scores compared to the control group, with a statistically significant difference between groups after the intervention. No significant difference was found between the groups in the pre-test scores, confirming baseline equivalence. These results suggest that simulation-transformed inquiry learning cycle enhances students' ability to construct scientific explanations more effectively than conventional inquiry learning mode. This approach offers a promising strategy for promoting science literacy and improving science learning outcomes in elementary education.

Keywords: Interactive simulation, inquiry-based learning, learning cycle, scientific competency, scientific explanation

Introduction

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In the rapidly evolving knowledge society, science literacy is no longer optional. Science literacy is essential for empowering individuals to make informed decisions, engage in civic discourse, and critically evaluate the growing volume of scientific information in digital and real-world contexts (Organization for Economic Co-operation and Development [OECD], 2018; National Research Council [NRC], 2012). A core element of science literacy is the ability to construct scientific explanations, a practice that involves articulating claims, supporting them with evidence, and reasoning through scientific principles (McNeill & Krajcik, 2008; NGSS Lead States, 2013). Cultivating this competency from early education enables learners not only to understand scientific phenomena but also to apply such understanding in diverse and meaningful contexts. Despite its importance, many elementary students struggle with scientific explanation competency, particularly in topics like electrical circuits, where abstract concepts are often taught through rote instruction rather than investigative practices. These limitations hinder students' conceptual understanding and restrict opportunities for developing scientific reasoning and inquiry skills (Chinn & Buckland, 2012; Sandoval, 2003). Therefore, there is an urgent need to transform science instruction to better support students in constructing coherent and evidence-based scientific explanations.

One promising response to this need is the integration of digital technologies, especially interactive science simulations, within inquiry-based learning environments. Advances in educational technology have enabled the development of interactive science simulations that model complex scientific phenomena with high fidelity and interactivity, supporting students in visualizing invisible processes, manipulating variables, and engaging in experimentation in safe, flexible environments (de Jong, Linn, & Zacharia, 2013; Rutten, van Joolingen, & van der Veen, 2012; Srisawasdi and Kroothkeaw, 2014). In particular, interactive science simulations, such as PhET, and similar platforms have demonstrated effectiveness in improving students' understanding of concepts such as electricity and circuits by providing real-time feedback and facilitating inquiry-driven exploration (Adams et al., 2015; Mahardika & Budiarso, 2020). Aligned with the constructivist learning theory, simulation-based inquiry learning mode encourages students to build knowledge through active engagement, problem-solving, and reflection, with scaffolding provided by the teacher (Lazonder & Harmsen, 2016). The 5E inquiry learning cycle—Engage, Explore, Explain, Elaborate, Evaluate (Bybee et al., 2006; Kapur & Bielaczyc, 2012)—has been widely adopted to structure inquiry-based science instruction and enhance its effectiveness when combined with digital tools (Srisawasdi and Kroothkeaw, 2014; Srisawasdi et al., 2016). By integrating simulations within this framework, students can investigate open-ended problems, test hypotheses, interpret data, and collaboratively construct scientific explanations with greater depth and accuracy (Srisawasdi and Sornkhatha, 2014; Srisawasdi et al., 2016).

This study responds to the call for more effective science instruction by investigating the use of a simulation-transformed 5E inquiry learning cycle in improving sixth-grade students' competency in constructing scientific explanations about electrical circuits. The guiding research question is: What is the effect of simulation-transformed 5E inquiry learning cycle on the development of scientific explanation competency among sixth-grade students studying electrical circuits, in comparison to conventional inquiry learning?

Literature Reviews

Simulation Technology in Science Education

The integration of simulation technology into science education has fundamentally transformed how students explore and internalize scientific concepts. Interactive science simulations allow learners to manipulate variables, observe immediate outcomes, and visualize invisible scientific phenomena, thereby enhancing conceptual understanding and addressing persistent misconceptions (de Jong, Linn, & Zacharia, 2013; Rutten, van Joolingen, & van der Veen, 2012). Such tools have proven especially valuable in topics involving microscopic or abstract processes.

Srisawasdi and colleagues have contributed significantly to this area, particularly in demonstrating how simulations enhance students' mental models and visualization skills. For instance, Suits and Srisawasdi (2013) showed that computer-simulated experiments can help students refine their mental models of complex molecular interactions, such as hydrogen bonding. Similarly, the integration of visualized simulations into context-aware ubiquitous learning environments has been found to enhance elementary students' engagement and contextual understanding in science learning (Srisawasdi et al., 2016). These innovations leverage mobile and digital platforms to expand the reach and adaptability of simulation-based science instruction.

The growing availability of open-access interactive simulations like PhET has further supported scalable implementation in classrooms worldwide (Adams et al., 2015). These tools, grounded in evidence-based design principles, offer high interactivity and feedback mechanisms that allow students to test hypotheses and construct meaning in a low-risk environment.

Simulation-based Inquiry Learning Pedagogies

Simulations reach their full instructional potential when incorporated into inquiry-based pedagogical frameworks that promote active learning, student autonomy, and scaffolded exploration. This combination which referred to as simulation-based inquiry learning has been widely supported by constructivist theorists, who emphasize learning as a process of knowledge construction through meaningful engagement and reflection (Furtak et al., 2012; Lazonder & Harmsen, 2016). In addition, the 5E inquiry learning cycle (Bybee et al., 2006), comprising Engage, Explore, Explain, Elaborate, and Evaluate, provides a systematic structure for implementing inquiry-based learning mode. When simulations are embedded into this cycle, they serve as cognitive tools that facilitate deep engagement with content through experimentation, observation, and reasoning (Zacharia, Olympiou, & Papaevripidou, 2008).

A series of empirical studies by Srisawasdi and collaborators illustrate the efficacy of simulation-based inquiry pedagogies. For example, Srisawasdi and Panjaburee (2015) found that the integration of formative assessment strategies within simulation-based inquiry significantly improved learning outcomes and conceptual understanding in secondary science classrooms. In another study, Srisawasdi and

Sornkhatha (2014) examined the impact of simulation-based inquiry in mobile learning contexts, showing its promise in enhancing accessibility and student engagement. Additionally, the dual-situated learning model combined real-world and simulated contexts was shown by Srisawasdi and Kroothkeaw (2014) to improve students' conceptual learning and retention of optics concepts. Together, these studies underscore the pedagogical strength of simulation-based inquiry learning, particularly when paired with formative feedback and situated learning principles.

Inquiry-based Science Learning and Learners' Scientific Explanation

A central goal of science education is to cultivate learners' capacity to construct scientific explanations, that is, to articulate claims, support them with evidence, and justify them using scientific principles (McNeill & Krajcik, 2006; NGSS, 2013). Developing this competency is crucial not only for mastering academic science but also for promoting science literacy, enabling students to participate in evidence-based reasoning and decision-making in everyday life (NRC, 2012; Osborne & Patterson, 2011).

Inquiry-based learning provides fertile ground for developing explanation skills, as it engages students in authentic scientific practices posing questions, designing experiments, interpreting data, and communicating findings (Chin & Osborne, 2010). Teachers play a facilitative role in scaffolding learners' reasoning and reflection processes throughout these activities (Abd-El-Khalick & Lederman, 2000). In addition, simulation environments support this development by allowing learners to generate and test hypotheses in dynamic, feedback-rich settings. Through simulation-enhanced inquiry, students are able to observe the consequences of their predictions, revise their ideas, and engage in iterative reasoning. Srisawasdi and Panjaburee (2015) observed that such environments, especially when enriched with formative assessment, promote deeper engagement in the construction of scientific explanations. Similarly, Srisawasdi and Sornkhatha (2014) reported that students using mobile simulations developed better explanatory skills through repeated opportunities to explore and reflect.

Furthermore, Srisawasdi and Kroothkeaw (2014) emphasized that simulation-based inquiry helps bridge the gap between theoretical and practical knowledge, supporting retention of scientific concepts and promoting learners' ability to apply reasoning to novel situations. These findings are echoed in the broader literature, which affirms that inquiry combined with digital simulations supports both epistemic and conceptual aspects of scientific explanation (Sandoval, 2003; Chinn & Malhotra, 2002).

■ Simulation-transformed 5E Inquiry Learning Cycle: A Proposed Approach

The Circuit Construction Kit: AC simulation proposed by PhET

Developing learners' competency in constructing scientific explanations requires more than rote memorization of scientific facts. Moreover, it demands engagement with phenomena through observation, evidence collection, and reasoning. In the context of electrical circuits, many elementary students struggle with abstract concepts such as current flow, voltage behavior, and the function of circuit components, often resulting in persistent misconceptions (McDermott & Shaffer, 1992; Rutten et al., 2012). Addressing these challenges requires pedagogical tools that make the invisible visible and promote inquiry-driven exploration.

To this end, this study employs the Circuit Construction Kit: AC simulation developed by the PhET interactive simulations project at the University of Colorado Boulder. This computer-based simulation provides an intuitive, interactive environment in which students can construct, manipulate, and observe alternating current (AC) electrical circuits. Through virtual experimentation, students engage in scientific inquiry practices, such as posing questions, formulating hypotheses, varying parameters (e.g., resistance, voltage, frequency), and interpreting data to build evidence-based conclusions. One of the key features of the simulation is its ability to visualize real-time current and voltage changes across various circuit components, including resistors, capacitors, and inductors, using animated charge carriers and responsive meters. These dynamic visualizations help students develop mechanistic understandings of how electrical systems behave under different conditions, bridging the gap between abstract theory and tangible observation. This is especially critical for promoting scientific explanation competency, as students must integrate what they observe with scientific principles to explain how and why a circuit behaves in a certain way.

For example, students using the simulation can build series and parallel circuits, observe the impact of component failure (such as a burnt-out bulb), and explain the functional differences between circuit configurations. In doing so, they are encouraged to construct explanations that consist of (i) Claims about how the circuit functions, (ii) Evidence derived from simulation output (e.g., voltage readings or current direction), and (iii) Reasoning that links this evidence to scientific concepts such as Ohm's Law or circuit continuity. These experiences are designed to scaffold the scientific explanation process, providing students with iterative opportunities to refine their ideas based on feedback from simulated experimentation. The simulation thus serves not only as a visualization tool but also as a cognitive amplifier that facilitates deep engagement with the scientific practices emphasized in contemporary science education frameworks (NGSS, 2013; NRC, 2012).

Overall, the Circuit Construction Kit: AC simulation (Figure 1) offers an ideal platform for embedding scientific explanation practices into inquiry-based learning. It aligns with constructivist pedagogy by enabling students to actively build and test their conceptual models, and it enhances their ability to articulate coherent, evidence-based explanations of scientific phenomena. In addition, the simulation allows students to explore voltage, current, and resistance dynamically by assembling circuits with virtual components such as light bulbs, switches, resistors, and power sources. It provides live feedback through numerical meters and animated charge flow to support scientific explanation construction.

The 5E Inquiry Learning Cycle with Interactive Science Simulation

To systematically develop students' scientific explanation competency, this study adopts a simulation-based inquiry learning approach grounded in the 5E instructional model (Bybee et al., 2006). This model supports a constructivist learning environment in which students actively construct knowledge through exploration, guided discovery, and reflection.

When integrated with simulation technology, the 5E model becomes a powerful pedagogical tool for cultivating scientific thinking skills. It enables learners to pose questions, design and conduct virtual investigations, and formulate explanations supported by evidence.

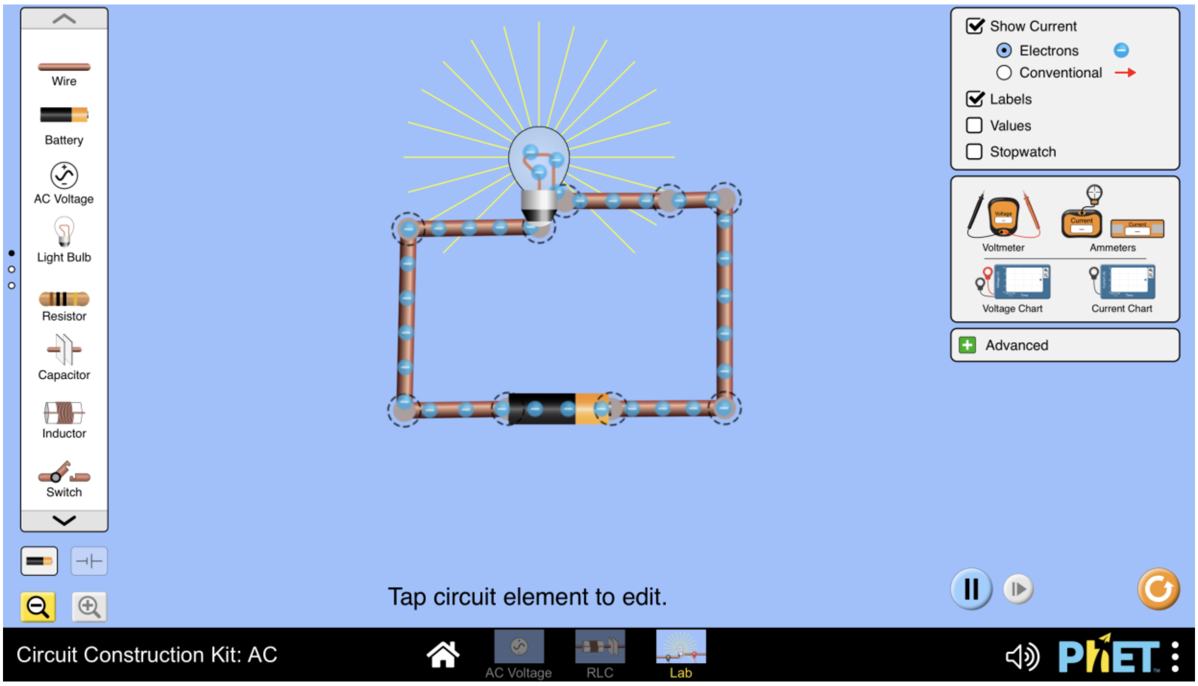

Figure *1*. Interface of the Circuit Construction Kit

Through the PhET Circuit Construction Kit: AC simulation, students can visualize and manipulate electrical circuit components in real-time, providing rich opportunities to collect and analyze data. This experience reinforces the claim-evidence-reasoning (CER) framework essential for constructing scientifically accurate explanations. Table 1 presents the alignment of each inquiry stage with pedagogically grounded simulation activities reinforcing both conceptual learning and the development of scientific explanation competency.

Table 1

The 5E Instructional Model Integrated into the Simulation-Based Inquiry Learning Approach Using the Circuit Construction Kit

5E Phase	Learning Stage	Instructional and Learning Activities
Engage	Defining the open-ended Problem	The teacher introduces a real-world scenario or puzzling phenomenon to spark curiosity and activate prior knowledge. For example: "*Why do all light bulbs go out in one house when one fails, but not in another?*" Students are

5E Phase	Learning Stage	Instructional and Learning Activities
		encouraged to generate questions and share initial ideas, initiating the process of constructing explanations.
Explore	Conducting simulation-based experiment	Students engage with the PhET Circuit Construction Kit: AC simulation to test circuit configurations (series vs. parallel), manipulate components, and observe dynamic responses. They gather empirical data, such as current flow, voltage, and brightness, and begin identifying patterns. These hands-on virtual investigations provide evidence for subsequent explanation building.
Explain	Providing background & facilitated discussion	Following exploration, the teacher scaffolds conceptual understanding by guiding a discussion of findings. Students articulate their observations, formulate claims, and collaboratively develop scientific reasoning with the teacher's support. Key concepts (e.g., current division, resistance in series/parallel) are clarified and linked to student-generated ideas, reinforcing conceptual accuracy.
Elaborate	Analyzing and communicating results	Learners apply their knowledge by refining their circuit designs to address the original problem. They construct scientific explanations using the claim-evidence-reasoning (CER) framework. This may include explaining how to redesign a circuit for the "little chick's house" to prevent complete blackout, and sharing reasoning through diagrams, presentations, or peer dialogue.
Evaluate	Concluding and synthesizing learning	The teacher facilitates reflection and peer feedback to assess the coherence and scientific accuracy of the students' explanations. Students revise their ideas based on critique and connect what they have learned to broader scientific principles. Both formative assessment and self-evaluation are used to gauge conceptual understanding and explanation competency.

Figure 2 illustrates the sequence of learning activities followed by students during the implementation of the simulation-based inquiry approach, specifically using the Circuit Construction Kit: AC simulation by PhET. Each image corresponds to a specific phase in the simulation-transformed 5E inquiry learning cycle, as detailed in Table 1.

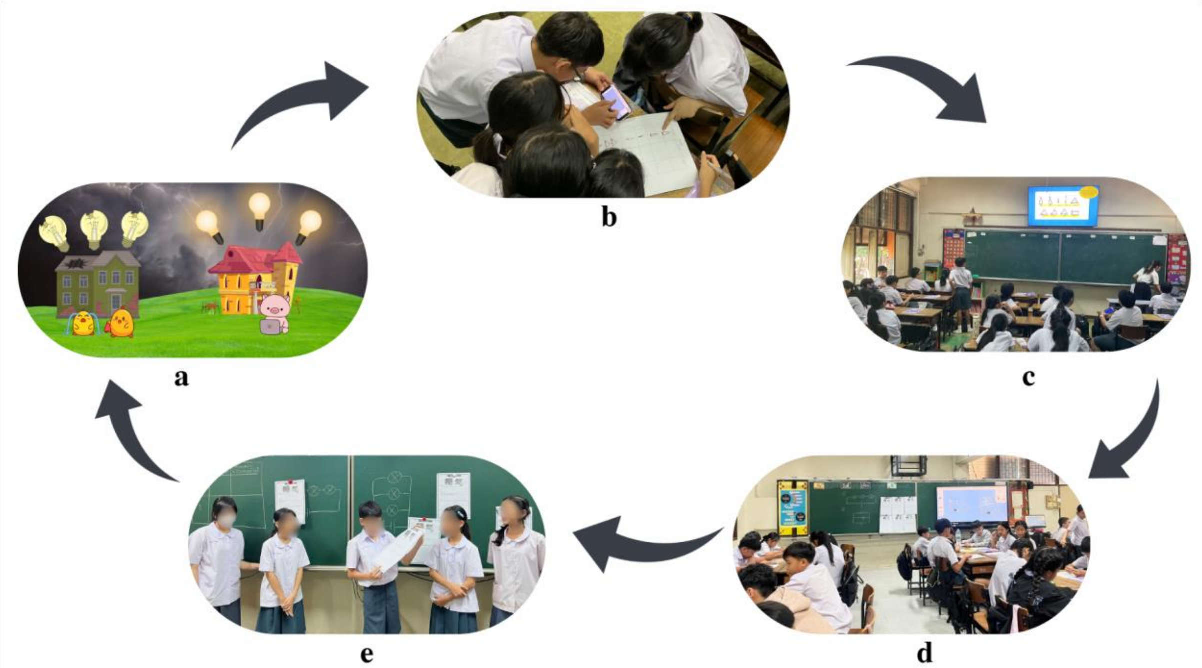

Figure *2*. Simulation-transformed Inquiry Learning Process Visualized through the 5E Inquiry Learning Cycle: (a) Engage—contextual problem scenario; (b) Explore—class-wide introduction to circuit concepts; (c) Explain—collaborative data analysis and explanation construction; (d) Elaborate—application through circuit redesign; (e) Evaluate—presentation and assessment of scientific explanations.

■ Research Methodology

Participant

The participants in this study consisted of sixth-grade students enrolled in the first semester of the 2024 academic year at a primary school in the Northeastern region of Thailand. A total of 77 students were selected through purposive sampling, a technique commonly used in educational research to access intact classrooms suited for instructional interventions (Fraenkel, Wallen, & Hyun, 2019). The two intact classrooms were randomly assigned to either the experimental group or the control group. The experimental group (n = 38) received instruction through the simulation-transformed 5E inquiry learning cycle, which integrated the Circuit Construction Kit: AC simulation by PhET within the 5E instructional model. In contrast, the control group (n = 39) was taught using a conventional inquiry learning approach, characterized by 5E inquiry learning cycle without digital technology and with traditional inquiry mode. To ensure internal validity, both groups were taught by the same science teacher throughout the study. Additionally, all students had comparable prior exposure to core science topics through the national science curriculum, which provided a consistent foundation for measuring learning gains resulting from the instructional intervention.

Measuring Tools

To evaluate students' ability to construct scientific explanations, an open-ended scientific explanation questionnaire was developed based on the CER framework (McNeill & Krajcik, 2006). The instrument was administered as both a pre-test and a post-test, targeting key concepts related to electrical circuits. The assessment included three scenario-based items, each designed to measure different components of scientific explanation. Each item consisted of three sub-questions:

- Claim (C) – Students identified a conclusion or explanation based on the scenario.
- Evidence (E) – Students provided relevant observations or data supporting the claim.
- Reasoning (R) – Students justified their claim by linking the evidence to appropriate scientific concepts.

Responses were scored using a rubric-based scoring guide, with each sub-question rated on a scale from 0 to 2, where 0 refers to inaccurate or no response, 1 refers to partial or underdeveloped response, and 2 refers to scientifically accurate and complete response. The total possible score reflected students' overall scientific explanation competency. The instrument's content validity was established through review by three expert science educators, and necessary revisions were made for clarity and alignment. Inter-rater reliability was ensured by having multiple raters independently score a subset of responses, achieving high agreement (Cohen's **K** > 0.80).

Data Analysis

Quantitative data analysis was conducted using IBM-SPSS version 29 to determine the effectiveness of the instructional intervention. Descriptive statistics, such as mean (M) and standard deviation (S.D.), were calculated for both pre- and post-test scores in each group. To test for statistically significant differences, normality tests were first conducted to examine the distribution of the data. Due to violations of normality, a non-parametric test, the Mann–Whitney U test and Wilcoxon signed-rank test, was employed to compare the scores between and within the experimental and control groups, respectively. This analytical approach enabled the study to determine not only the effectiveness of the simulation-transformed 5E inquiry learning approach but also its impact on the development of students' scientific explanation competency compared to conventional instructional methods.

■ Results

This section presents the findings of the study and interprets them in light of the research question: What is the effect of simulation-transformed 5E inquiry learning cycle on the development of scientific explanation competency among sixth-grade students studying electrical circuits, in comparison to conventional inquiry learning? Table 2 displays the descriptive and inferential statistics for the pre-test and post-test scores of both the experimental and control groups on the scientific explanation assessment.

The pre-test results revealed no statistically significant difference between the two groups (z = -0.206, p = .837), indicating that students in both groups began with comparable levels of prior knowledge about electrical circuits. However, the post-test scores demonstrated a statistically significant difference in favor of the experimental group (z = -6.793, p < .001). The experimental group, taught using the simulation-transformed inquiry learning cycle, achieved a mean post-test score of 15.29 (S.D. = 1.23), whereas the control group, taught using conventional inquiry method, scored a mean of 12.18 (S.D. = 1.50). This suggests that the simulation-based inquiry approach had a significant positive effect on students' scientific explanation performance.

Table 2

Comparison of Pre-test and Post-test Results between Experimental and Control Groups.

Assessment	Experimental group			Control group			z	Asymp. Sig. (2-tailed
	n	M	S.D.	n	M	S.D.		
Pre-test	38	9.24	1.88	39	9.13	2.66	-0.206	.837
Post-test	38	15.29	1.23	39	12.18	1.50	-6.793	<.001*

* $p < .05$

The findings from this study indicate that sixth-grade students who engaged in a simulation-transformed 5E inquiry learning cycle demonstrated significantly greater improvements in scientific explanation competency compared to their peers who experienced conventional inquiry learning mode. This reinforces the educational value of combining digital learning technologies with inquiry-oriented pedagogical strategies to enhance students' ability to construct coherent, evidence-based scientific explanations. Additionally, a primary contributor to this learning gain was the implementation of the Circuit Construction Kit: AC simulation by PhET, which provided students with an interactive and manipulable environment in which they could experiment with virtual electrical circuits. The dynamic visual feedback from the simulation enabled students to observe the real-time behavior of current and voltage under varying circuit conditions, bridging the gap between abstract theoretical content and tangible scientific phenomena. These interactive experiences allowed students to explore, test, and revise their ideas—a core process in scientific reasoning.

In addition to between-group comparisons, within-group analysis was conducted to examine the effectiveness of the instructional approach in each group. As shown in Table 3, both the control group and the experimental group demonstrated statistically significant improvements from pre-test to post-test on the scientific explanation assessment. The control group showed an increase in mean score from M = 9.13 (S.D. = 2.66) to M = 12.18 (S.D. = 1.50), with a z-value of -4.921 and p < .001. Similarly, the experimental group improved from M = 9.24 (S.D. = 1.88) to M = 15.29 (S.D. = 1.23), with a z-value of -5.396 and p < .001.

Table 3

Comparison of Pre-test and Post-test Results between Experimental and Control Groups.

Assessment	Pre-test			Post-test			z	Asymp. Sig. (2-tailed)
	n	M	S.D.	n	M	S.D.		
Control group	39	9.13	2.66	39	12.18	1.50	-4.921	<.001*
Experimental group	38	9.24	1.88	38	15.29	1.23	-5.396	<.001*

* $p < .05$

These findings confirm that both instructional methods, conventional 5E and simulation-transformed 5E inquiry learning cycle, contributed to student learning gains. However, the larger effect size and higher post-test mean score in the experimental group indicate a more substantial impact of the simulation-transformed 5E inquiry learning cycle on students' scientific explanation competency. This within-group analysis complements the earlier between-group results and provides further evidence of the model's effectiveness in supporting scientific explanation competency in elementary science education.

The integration of the CER framework within the 5E inquiry learning cycle further scaffolded students' cognitive engagement. As learners progressed from the engagement phase to the evaluation phase, they actively constructed scientific explanations by linking experimental evidence to claims and justifying their conclusions with scientific reasoning. This approach mirrors authentic scientific practices and has been shown to foster deeper conceptual understanding and explanation competency, as also supported by McNeill and Krajcik (2008). The effectiveness of this approach is corroborated by similar findings in literature. For example, Sritawan and Srisawasdi (2023) found that a seamless STEM learning model on Newton's Laws of Motion significantly improved secondary students' scientific explanation skills by integrating real-world contexts and digital tools across learning phases. Like the current study, their approach emphasized meaningful engagement through inquiry and visualization, leading to improved coherence and structure in students' scientific explanations. This suggests that technology-mediated learning environments designed with continuous support across phases of inquiry can lead to significant gains in scientific explanation competency.

Similarly, Sangprasert et al. (2018) reported positive effects of a 7E inquiry-based learning combined with a scientific explanation strategy on students' learning achievement and ability to explain photosynthesis. Their findings highlight the importance of explicit instructional strategies that focus on constructing explanations using scientific evidence and reasoning focus that parallels the structured inquiry framework used in the present study. Their emphasis on strategic questioning, evidence collection, and reasoning construction underscores the necessity of guided pedagogical structures for fostering advanced cognitive processes. Moreover, the results align closely with those of Thinnongwaeng, Srisawasdi, and Chaipidech (2024), who found that integrating mobile-assisted inquiry learning with interactive videos significantly boosted seventh-grade students' scientific explanation competency and content understanding. The success of their model illustrates how digital tools, when effectively embedded in inquiry learning tasks, provide opportunities for iterative sense-making and explanation building, particularly through visual scaffolding and responsive feedback mechanisms. Their research supports the notion that interactive and multimodal learning environments can enhance both conceptual mastery and reasoning skills.

Although the control group in this study also demonstrated improvement, the comparatively larger gains observed in the experimental group emphasize that conventional inquiry-based learning modes may be insufficient for cultivating scientific explanation competency. The 5E inquiry-based use of simulations, by contrast, actively engages learners in the construction and validation of knowledge through firsthand investigation and scientific argumentation. Overall, this study contributes to the growing body of evidence supporting the integration of interactive simulations within inquiry learning frameworks to enhance students' scientific literacy and explanation competency. It affirms that pedagogically structured, digitally enriched science instruction, when grounded in constructivist principles and aligned with models like CER and 5E, can effectively transform abstract content into meaningful, student-generated scientific understanding.

■ Discussion

The findings from this study affirm that the simulation-transformed 5E inquiry learning cycle significantly enhances students' competency in constructing scientific explanations in the context of electrical circuits. The experimental group demonstrated a statistically significant increase in post-test scores compared to the control group, indicating that students benefited from engaging with interactive science simulations and structured inquiry tasks like 5E model. Although both groups showed improvement from pre-test to post-test ($p < .001$), the greater magnitude of gains in the experimental group highlights the superior effectiveness of this instructional approach in promoting students' scientific competency.

These findings are consistent with the theoretical assertion by McNeill and Krajcik (2008) that structured inquiry learning experiences, particularly those incorporating the CER model, foster deeper engagement in scientific reasoning and explanation construction than traditional lecture-based instruction. In this study, students in the experimental group were guided through all phases of the 5E model, allowing them to build explanations through iterative hypothesis testing, evidence gathering, and reflective reasoning. The integration of the CER framework within this process scaffolded learners' cognitive development and helped them articulate scientifically accurate claims supported by data and reasoning. The PhET interactive simulation played a central role in enhancing students' learning experiences. Its interactive and visual affordances enabled students to manipulate variables, visualize abstract phenomena such as current flow and voltage, and observe the outcomes in real time. These features are especially effective in making invisible scientific concepts more accessible, facilitating the construction of mental models, and supporting evidence-based explanation (Srisawasdi & Panjaburee, 2015; Suits & Srisawasdi, 2013). As a result, students were not only more engaged but also more capable of connecting empirical data to scientific principles, key components of explanation competency.

The results of this study align with recent research emphasizing the importance of technology-enhanced inquiry learning environments. For example, Sritawan and Srisawasdi (2023) found that seamless STEM learning using real-world contexts and digital tools significantly improved students' explanation skills. Similarly, Thinnongwaeng, Srisawasdi, and Chaipidech (2024) reported that integrating mobile-assisted inquiry with interactive videos led to substantial gains in both scientific understanding and explanatory reasoning. These studies support the idea that digital scaffolding embedded within inquiry cycles enhances iterative sense-making and reflection. Additionally, the work of Sangprasert et al. (2018) reinforces the importance of incorporating explicit explanation strategies in inquiry-based instruction, demonstrating that the use of structured questioning and evidence construction improves students' ability to explain scientific phenomena.

Despite the observed improvement in the control group, likely due to the reinforcement of foundational knowledge through repeated exposure, the comparatively smaller effect size suggests that conventional methods may not be sufficient to cultivate the higher-order reasoning and conceptual integration needed for scientific explanation. In contrast, the simulation-transformed 5E inquiry learning cycle appears to offer a cognitively enriched learning environment that fosters deeper engagement and more meaningful learning outcomes. These findings support the broader pedagogical implication that simulations, when embedded in inquiry-oriented frameworks, can function as powerful cognitive tools. They encourage learners not only to explore and experiment but also to articulate and defend their scientific ideas with clarity and logic. This study contributes to the expanding body of evidence demonstrating that digitally enriched, inquiry-driven science instruction—grounded in constructivist principles and aligned with current educational standards such as NGSS (2013) and the NRC Framework (2012)—can effectively enhance both scientific literacy and explanation competency at the primary level.

■ Conclusion, Limitations, and Future Research

This study examined the impact of a simulation-based guided inquiry learning approach, supported by the CER framework and the 5E inquiry learning cycle, on sixth-grade students' competency in constructing scientific explanations about electrical circuits. The results provide compelling evidence that this integrated instructional approach significantly enhances students' ability to make claims, support them with empirical evidence, and reason scientifically when compared to conventional teaching methods. The use of interactive simulations enabled learners to visualize abstract concepts and engage in authentic scientific practices through hands-on experimentation, hypothesis testing, and reflection. These cognitive processes are essential not only for science learning but also for developing science literacy more broadly. While the control group showed statistically significant learning gains, the experimental group demonstrated significantly greater improvement, confirming the value of combining digital tools with structured inquiry-based pedagogy. These findings are consistent with a growing body of research supporting technology-enhanced inquiry learning as a means to foster deeper conceptual understanding and explanatory reasoning in school science.

However, the study is subject to several limitations. First, the sample size was limited to two classrooms from a single school, which may constrain the generalizability of the findings. Second, the study focused exclusively on one science topic—electrical circuits—and assessed short-term learning outcomes. Future studies should investigate the effectiveness of this approach across a broader range of scientific topics and age groups, as well as its long-term impact on the retention and transfer of explanation skills. Incorporating qualitative data, such as student interviews, classroom observations, or analysis of student discourse, could also enrich our understanding of how learners engage with the CER process and digital simulations.

In conclusion, this study supports the integration of simulation-transformed 5E inquiry learning cycle as a pedagogically sound and empirically effective approach for promoting scientific explanation competency in elementary education. By aligning digital learning environments with structured inquiry models, educators can provide meaningful, cognitively rich experiences that cultivate critical thinking, reasoning, and communication—skills that are foundational for learners in the 21st-century science classroom. Future research should continue to explore scalable models and implementation strategies that bring these benefits to diverse educational contexts.

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