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Improving Students' Digital Literacy through the Physics Simulation Interactive Carnot-Sim Application (PhySIC-SIM)

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ABSTRACT

This study aims to analyze the effect of using the PhySIC-SIM interactive simulation application on improving the digital literacy of prospective physics teacher students in learning the Carnot cycle. This study used a quasi-experimental method with a single-group pretest-posttest design involving 19 students enrolled in a thermodynamics course. The instrument used was a digital literacy test based on nine indicators, including understanding basic concepts, unit operation configuration, creativity optimization, revision management, communication of results, database selection, and validity evaluation. Data were analyzed using descriptive statistics, the N-Gain test, a paired sample t-test, and effect size analysis (Cohen's d). The results showed that the average student score increased from 13.11 (52.44%) in the pretest to 21.63 (87%) in the posttest. The average N-Gain value of 0.71 indicates a high improvement category. Furthermore, the paired sample t-test revealed a significance value of $p < 0.05$, indicating a significant difference between the pretest and posttest scores. The effect size calculation yielded a Cohen's d value of 3.16, indicating a very large effect. This finding suggests that PhysIC-SIM effectively improves students' digital literacy. Nevertheless, this study is limited by the use of a one-group pretest-posttest design without a control group and the relatively small sample size, which may limit the generalizability of the findings. Therefore, future studies are recommended to involve larger samples and experimental comparison groups to obtain more comprehensive evidence regarding the effectiveness of PhySIC-SIM.

Keywords: Carnot cycle, digital literacy, interactive simulation, PhySIC-SIM

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INTRODUCTION

Digital literacy is a crucial skill in today's education, particularly in the context of learning that utilizes technology. Digital literacy encompasses more than just the technical ability to operate digital devices; it also encompasses the ability to think and interact socially, capturing, evaluating, and conveying information accurately and effectively (Ng, 2012; Eshet-Alkalai, 2004). Information and Communication Technology (ICT) is also beneficial for students to become active learners by creating content for viewers throughout the archipelago or the world (Rahmawati & Wolo, 2022). Recent developments indicate that digital literacy skills are closely related to critical thinking and problem-solving skills in the digital world (van Laar et al., 2020; Spante et al., 2023). In higher education, especially for prospective teachers, digital literacy is crucial because it helps integrate technology into the learning process. Recent studies have shown that teachers' digital readiness impacts on the quality of technology-based learning (Instefjord & Munthe, 2020; Falloon, 2020; Mane, 2025; Mahesti et al., 2025). Therefore, improving digital literacy skills for prospective teachers is crucial and must be implemented immediately. When studying physics, especially abstract topics like the Carnot cycle, students often struggle to grasp concepts due to a lack of visualization and hands-on experimental experience. Recent research suggests that using visualization and simulation technology can help overcome these challenges by providing a moving image of abstract concepts (Makransky et al., 2020; Jensen & Konradsen, 2021).

Interactive simulations are a great way to learn science. They help students explore, change variables, and directly observe phenomena that are difficult to see in real life (Rutten et al., 2012; Smetana & Bell, 2012). Recent research has shown that the use of technology-based simulations can increase student engagement, conceptual understanding, and digital skills (Kade et al., 2024; Radianti et al., 2020; Parong & Mayer, 2021; Wahidin et al., 2025). Besides helping students understand concepts better, simulations also help improve digital literacy. Simulation environments require students to actively interact with technology, analyze data, and communicate results digitally. This is consistent with research showing that learning using technology can significantly improve students' digital skills (Spante et al., 2023).

In physics learning, the use of interactive simulation media such as Physic-SIM is a digital innovation that can support a more active, visual, and contextual learning process. Physic-SIM is an interactive simulation-based learning medium developed to help students or learners understand physics concepts visually, exploratively, and contextually. Physic-SIM is designed to help students understand abstract physics concepts through dynamic visualization, variable manipulation, and virtual experiments that allow students to explore physics phenomena independently. Through the use of digital simulations, students not only gain a better conceptual understanding but also engage in technology-based learning activities that encourage digital literacy skills, such as accessing information, interpreting data, analyzing simulation results, and using technology critically in problem-solving. In the context of 21st-century physics learning, the integration of media such as Physic-SIM can create a more interactive and adaptive learning experience that supports the development of students' scientific thinking skills and digital literacy simultaneously.

The Carnot cycle is one of the fundamental topics in thermodynamics that explains the relationship between heat, work, and energy conversion efficiency. However, learning the Carnot cycle is often considered difficult by students because the concepts are abstract, mathematical, and involve dynamic thermodynamic processes that are not directly observable in real-life situations. Students frequently experience difficulties in understanding the relationships between pressure, temperature, volume, and entropy during each stage of the cycle. Conventional learning methods that rely heavily on lectures and static illustrations are often insufficient to support conceptual visualization and active exploration. As a result, students tend to memorize formulas without fully understanding the underlying thermodynamic processes. Recent studies suggest that visualization and simulation technologies can help overcome these difficulties by providing dynamic representations of abstract concepts and enabling students to interact directly with thermodynamic processes (Makransky et al., 2020; Jensen & Konradsen, 2021).

In addition to conceptual challenges, the demands of 21st-century education require prospective physics teachers not only to master scientific concepts but also to possess strong digital literacy skills. Digital literacy involves the ability to access, analyze, evaluate, communicate, and utilize digital information critically and responsibly (Ng, 2012; Eshet-Alkalai, 2004). Recent developments indicate that digital literacy is closely related to critical thinking, problem-solving, and technology-based learning competencies (van Laar et al., 2020; Spante et al., 2023). For prospective physics teachers, digital literacy is essential because future learning environments increasingly integrate digital technologies, simulations, and online learning platforms. Teachers with adequate digital literacy are better prepared to design interactive learning experiences, integrate educational technology effectively, and guide students in technology-supported scientific inquiry (Instefjord & Munthe, 2017; Falloon, 2020). Therefore, physics teacher education programs need learning approaches that simultaneously develop conceptual understanding and digital literacy competencies.

Interactive simulations have been widely recognized as effective tools for science learning because they allow students to explore phenomena, manipulate variables, and directly observe processes that are difficult to visualize in real life (Rutten et al., 2012; Smetana & Bell, 2012). Recent studies have also shown that simulation-based learning can improve conceptual understanding, student engagement, and digital competencies (Radianti et al., 2020; Parong & Mayer, 2021). Furthermore, recent developments in technology-based learning demonstrate that the effectiveness of simulations depends not only on visual presentation but also on how students actively interact with digital environments. Exploratory and task-based interactions can increase students' cognitive engagement and strengthen their digital literacy skills (Makransky et al., 2021; Radianti et al., 2020). In addition, technology-integrated learning encourages students to develop higher-order thinking skills, such as evaluating information, interpreting data, and making evidence-based decisions (van Laar et al., 2020).

However, several recent studies indicate that not all aspects of digital literacy develop equally in technology-based learning environments, particularly evaluation and reflection skills (Spante et al., 2023; Falloon, 2020). Previous studies have generally focused on improving learning outcomes or digital literacy in a broad sense, without analyzing the development of digital literacy based on specific indicators. In fact, digital literacy is a multidimensional construct that develops differently across its technical, cognitive, and social dimensions (Ng, 2012; van Laar et al., 2020). Moreover, research examining digital literacy development specifically in the context of physics simulations remains limited, especially in thermodynamics learning and prospective teacher education contexts. Consequently, there is still a gap in understanding how simulation-based learning contributes to the development of specific digital literacy indicators such as communication, creativity, collaboration, evaluation, and technology-based problem-solving.

To address this gap, this study introduces PhySIC-SIM, an interactive simulation application specifically designed for Carnot cycle learning. Unlike general simulation platforms that mainly emphasize conceptual visualization, PhySIC-SIM integrates dynamic thermodynamic visualization with digital literacy-oriented learning activities. The application enables students to manipulate variables, observe thermodynamic changes in real time, analyze simulation data, communicate findings, and engage in technology-based problem-solving. Thus, the novelty of PhySIC-SIM lies not only in its focus on Carnot cycle visualization but also in its integration of digital literacy development within simulation-based physics learning. In addition, the application is specifically implemented in the context of prospective physics teacher education, making it relevant to the development of pedagogical and technological competencies required in 21st-century science education. Based on these issues and research gaps, this study seeks to answer the following research questions:

1. Does the use of PhySIC-SIM significantly improve the digital literacy of prospective physics teacher students in the Carnot cycle learning?

2. How effective is PhySIC-SIM in improving students' digital literacy based on N-gain and effect size analysis?
3. Which indicators of digital literacy show the highest and lowest improvement after the implementation of PhySIC-SIM?
4. How does simulation-based learning through PhySIC-SIM contribute to the development of exploratory, operational, and evaluative digital literacy skills?

METHODS

This study employed a quasi-experimental method using a one-group pretest-posttest design to investigate the effect of the PhySIC-SIM interactive simulation application on improving students' digital literacy in Carnot cycle learning. In this design, students were given a pretest before the implementation of the learning treatment and a posttest after the learning process was completed. The design enabled the researchers to compare students' digital literacy achievement before and after the use of PhySIC-SIM. Although this design does not involve a control group, it is appropriate for preliminary studies aimed at identifying the potential effectiveness of an educational intervention in authentic classroom settings.

The participants in this study consisted of 19 prospective physics teacher students enrolled in a thermodynamics course at a university in Indonesia. The participants were selected using purposive sampling because they had prior experience using digital learning technologies and had studied basic thermodynamics concepts relevant to the Carnot cycle. The participants represented undergraduate students preparing to become future physics teachers, making them relevant subjects for examining the integration of digital literacy and technology-based physics learning. PhySIC-SIM is an interactive physics simulation application specifically developed for learning the Carnot cycle. The application integrates dynamic thermodynamic visualization, interactive variable manipulation, and simulation-based exploration activities. Through PhySIC-SIM, students can observe changes in pressure, temperature, heat transfer, and efficiency in real time while exploring the relationships among thermodynamic variables. Unlike general simulation applications that mainly emphasize conceptual visualization, PhySIC-SIM was designed to support digital literacy-oriented learning activities, including data interpretation, digital communication, collaborative exploration, and technology-based problem solving. The application also encourages students to engage actively with the digital environment through exploratory and inquiry-based learning processes.

The learning procedure was conducted in several stages. In the first stage, students completed a pretest to measure their initial digital literacy skills before the intervention. In the second stage, students participated in simulation-based learning activities using PhySIC-SIM during Carnot cycle instruction. During the learning process, students explored simulation features, manipulated thermodynamic variables, observed simulation outcomes, analyzed data generated from the simulation, and discussed their findings with peers. The lecturer facilitated learning activities by guiding students in interpreting simulation results and encouraging reflective discussions related to thermodynamic concepts and digital problem-solving. After completing the learning activities, students were given a posttest to evaluate changes in their digital literacy skills after the intervention. The instrument used in this study was a digital literacy test consisting of 25 items developed based on nine indicators: (1) understanding basic concepts, (2) configuring operating units, (3) optimizing creativity, (4) dividing projects, (5) managing revisions, (6) communicating results, (7) providing feedback, (8) selecting databases, and (9) evaluating validity. These indicators were adapted from multidimensional digital literacy frameworks proposed by Ng and van Laar, which emphasize technical, cognitive, and social dimensions of digital competence in technology-based learning environments. The instrument blueprint was designed to ensure that each indicator was represented proportionally in the test items. The questions were developed in the context of simulation-based thermodynamics learning using PhySIC-SIM. The instrument consisted of multiple-choice and scenario-based items that required students to analyze simulation outputs, interpret digital information, evaluate data validity, communicate findings, and make decisions based on simulation results. Each correct answer was scored one point, while incorrect answers received zero points, resulting in a maximum possible score of 25. Examples of instrument items included interpreting changes in thermodynamic variables displayed in the simulation, selecting appropriate digital data sources related to the Carnot cycle, evaluating the validity of simulation-generated results, and determining appropriate revisions to simulation procedures based on observed outcomes. To establish content validity, the instrument was evaluated by three experts in physics education and educational technology. The experts reviewed the relevance, clarity, language appropriateness, and alignment of each item with the intended digital literacy indicators and research objectives. Revisions were conducted based on expert suggestions before the instrument was administered to participants. The content validity process indicated that all items were considered appropriate for measuring digital literacy within simulation-based learning contexts.

Construct validity was examined through item analysis by assessing the correlation between item scores and total scores. Items with low correlations were revised to improve clarity and alignment with the intended indicators. In addition, reliability analysis was conducted using Cronbach's alpha coefficient to determine the internal consistency of the instrument. The reliability coefficient indicated that the instrument had acceptable reliability for educational research purposes. Item quality analysis was also conducted to evaluate the level of difficulty and discriminating power of the test items. The difficulty index analysis showed that the instrument contained a balanced distribution of easy, moderate, and difficult items. Meanwhile, the discrimination index analysis demonstrated that most items were able to distinguish effectively between students with high and low digital literacy abilities. Therefore, the instrument was considered suitable for measuring students' digital literacy skills in the context of PhySIC-SIM-based learning. Data analysis in this study was conducted in several stages. First, descriptive statistical analysis was used to determine the mean, median, standard deviation, minimum score, maximum score, and percentage of students' pretest and posttest scores. Second, the normalized gain (N-Gain) test was conducted to determine the level of improvement in students' digital literacy after the intervention. Third, a paired sample t-test was used to determine whether there was a statistically significant difference between pretest and posttest scores. Finally, effect size analysis using Cohen's d was conducted to measure the magnitude of the effect of PhySIC-SIM on students' digital literacy improvement. Through these analyses, the study aimed to provide both statistical and practical evidence regarding the effectiveness of simulation-based learning using PhySIC-SIM. In general, the research flow can be seen in Figure 1.

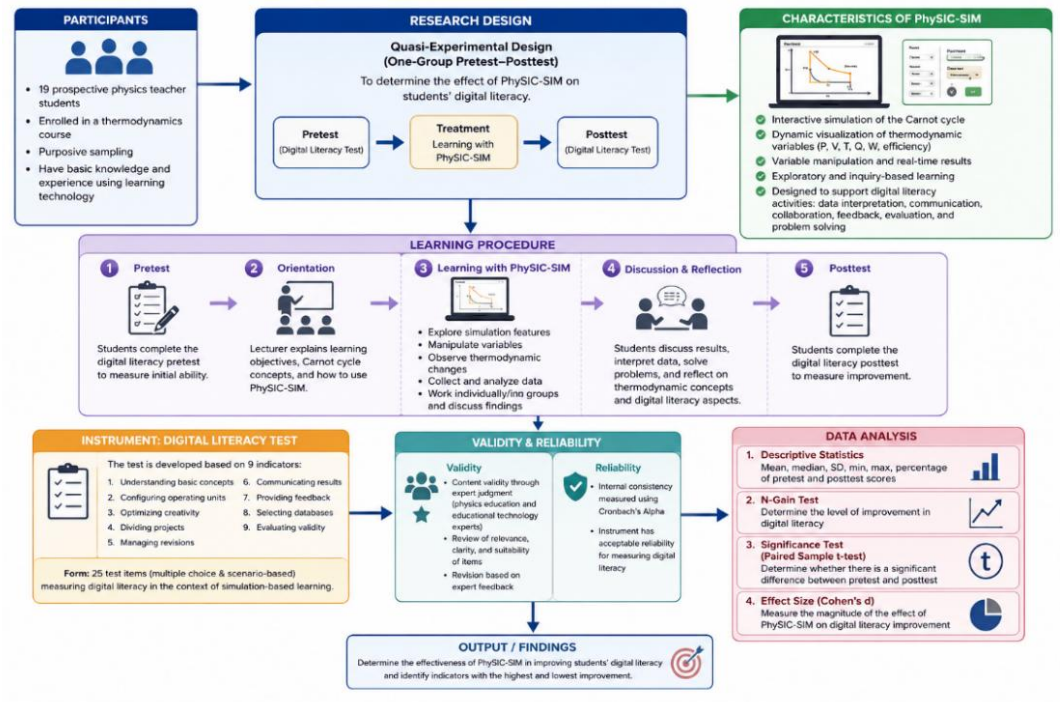

Figure 1. Research methodology flowchart of PhySIC-SIM-based learning

RESULT AND DISCUSSION

To determine students' digital literacy achievements before and after learning using PhysIC-SIM, descriptive statistical analysis was conducted on the students' pretest and posttest results. The results of this analysis are presented in Table 1 and Table 2.

Table 1. Descriptive statistics for the digital literacy pretest

Statistics	Score
Number of Respondents	19
Number of Questions	25
Average	13.11
Median	13
Standard Deviation	2.34
Minimum Score	9
Maximum Score	17
Average Percentage	52.44%

Based on Table 1, the average digital literacy score for students was 13.11 out of a maximum score of 25, representing a percentage of 52.44%. This indicates that students' initial digital literacy skills are in the moderate to low category. The median score of 13, which is close to the mean, indicates that the data distribution is relatively symmetrical. The standard deviation of 2.34 indicates that the variation in student abilities is not too high, so students' digital literacy skills tend to be within a relatively homogeneous range. The minimum score of 9 and the maximum score of 17 indicate that no students have achieved the optimal score, so in general, students' digital literacy skills still need to be improved.

Table 2. Descriptive statistics of digital literacy posttest

Statistics	Score
Number of Respondents	19
Number of Questions	25
Average	21.63
Median	21
Standard Deviation	1.27

Minimum Score	19
Maximum Score	24
Average Percentage	87 %

Based on Table 2, the average digital literacy score for students was 21.63, indicating an increase compared to the average pretest score of 13.11. The average percentage of 87% indicates that students' digital literacy skills after learning are in the medium/high category. The median value of 21, which is close to the average, indicates that the data distribution is relatively balanced. The standard deviation of 1.27 indicates that the variation in student abilities is still within a controllable range. The minimum and maximum scores of 19 and 24, respectively, indicate that some students have achieved a better level of digital literacy mastery than their initial condition.

The improvement analysis was conducted by comparing pretest and posttest scores, calculating gain and normalized gain (N-gain), and supplemented with inferential statistical tests and effect sizes. To clarify the differences in students' digital literacy achievements before and after the learning process, a comparison graph of pretest and posttest scores for each respondent is presented. This graph can be seen in Figure 2.

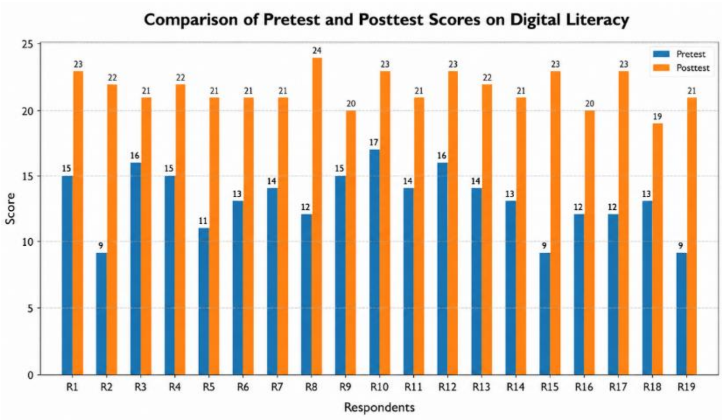

Figure 2. Comparison of students' digital literacy pretest and posttest scores

To determine the level of improvement in students' digital literacy in more detail, a normalized gain (N-Gain) analysis was conducted on each respondent. The results of the N-Gain calculation are presented in Table 3.

Table 3. Results of the calculation of student digital literacy N-Gain for each respondent

Respondent	Pre-test	Post-test	N-Gain	Category
R1	15	23	0.80	High
R2	9	22	0.81	High
R3	16	21	0.56	Medium
R4	15	22	0.70	High
R5	11	21	0.71	High
R6	13	21	0.67	Medium
R7	14	21	0.64	Medium
R8	12	24	0.92	High
R9	15	20	0.50	Medium
R10	17	23	0.75	High
R11	14	21	0.64	Medium
R12	16	23	0.78	High
R13	14	22	0.73	High
R14	13	21	0.67	Medium
R15	9	23	0.88	High
R16	12	20	0.62	Medium
R17	12	23	0.85	High

R18	13	19	0.50	Medium
R19	9	21	0.75	High

Based on the data in Table 3, the N-Gain value for each respondent ranges from 0.50 to 0.92. To obtain a general overview, the average N-Gain is calculated as follows:

$$Average\ N - Gain = \frac{13.48}{19} = 0.71$$

The average N-Gain value of 0.71 is in the high category. This indicates that students' digital literacy improved significantly after learning using PhySIC-SIM. To clarify the distribution of digital literacy improvement among respondents, a graph of N-Gain values based on the calculations for each respondent is presented in Figure 3.

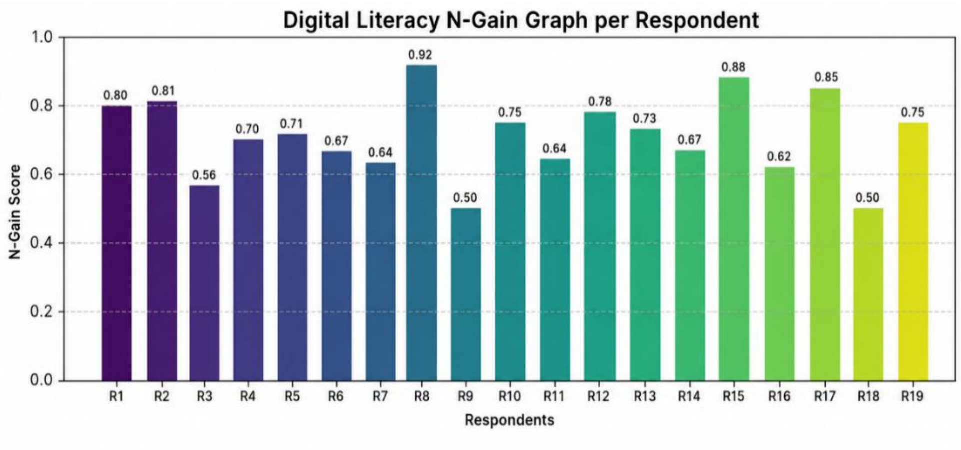

Figure 3. N-Gain graph of student digital literacy per respondent

Overall, the N-Gain value indicates that learning using PhySIC-SIM is effective in improving students' digital literacy.

After analyzing the increase in digital literacy based on a comparison of pretest and posttest scores and the N-Gain calculation, a statistical significance test was conducted to determine whether the increase was significant. The paired sample t-test was used in this study because the data came from the same group and met the assumption of normality. The results are presented in Table 4.

Table 4. Results of the paired sample t-test on digital literacy

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Pretest LD - Posttest LD	-8.526	2.695	0.618	-9.825	-7.227	-13.790	18	0.000

Based on the results of the paired sample t-test in Table 4, a significance value of 0.000 ($p < 0.05$) was obtained. This indicates a significant difference between the pretest and posttest scores on students' digital literacy. To complement the results of the significance test, the analysis continued with an effect size calculation to determine the strength of the influence of learning using PhySIC-SIM on improving students' digital literacy. The effect size calculation in this study used Cohen's d equation on paired data.

$$d = \frac{Mean\ Difference}{standard\ deviation}$$

$$d = \frac{8.526}{2.695} = 3{,}16$$

Based on the effect size calculation using Cohen's d, a value of 3.16 was obtained. This value indicates that the impact of learning using PhySIC-SIM on improving students' digital literacy is very large, so the improvement is not only statistically significant but also has strong practical significance.

The results of the study indicate that the use of PhySIC-SIM in Carnot cycle learning significantly improved students' digital literacy. This improvement was not only evident in the difference between pretest and posttest scores but also supported by the high N-Gain value and very large effect size. This demonstrates that simulation-based learning is not only statistically effective but also has a strong practical impact on digital literacy development.

Theoretically, this increase in digital literacy can be explained through a multidimensional digital literacy framework that encompasses technical, cognitive, and social aspects (Ng, 2012). In the context of this study, the use of PhySIC-SIM allows students to develop technical skills through direct interaction with simulations, cognitive skills through analysis of simulation results, and social skills through communication and collaboration activities. Thus, the results of this study reinforce the view that digital literacy develops integratively through technology-based learning experiences. Furthermore, the improvements that occur can also be explained through constructivism theory, which emphasizes that learning occurs through an active process of constructing knowledge (Piaget; Vygotsky). In learning using PhySIC-SIM, students do not simply receive information passively but actively explore, manipulate variables, and interpret simulation results. These activities allow students to build conceptual understanding while simultaneously developing digital skills.

When viewed based on indicators, the research results indicate that improvements in digital literacy are not evenly distributed. Indicators related to exploratory and operational aspects, such as optimizing creativity, configuring operating units, and communicating results, show higher improvements than other indicators. This suggests that interactive simulations are highly effective in developing exploratory and hands-on skills. These findings align with previous research that suggests simulations provide a learning environment that allows students to freely explore and experiment with various possibilities (de Jong & van Joolingen, 1998). Through this exploration, students can enhance their creativity and ability to use technology effectively.

In contrast, indicators such as managing revisions and selecting databases showed relatively lower and non-statistically significant improvements. This suggests that these skills require higher-order thinking skills, such as evaluation, reflection, and data-driven decision-making. These skills do not develop instantly and require more intensive practice and complex learning experiences. This finding is also supported by recent research showing that technology-based learning tends to be more effective in developing operational skills than evaluative skills (Spante et al., 2023). Therefore, additional learning strategies, such as scaffolding, reflection, and analysis-based assignments, are needed to improve students' evaluative skills. Furthermore, the very large effect size indicates that the use of PhySIC-SIM has a strong influence on improving digital literacy. This indicates that simulation functions not only as a learning medium but also as a tool capable of encouraging active student engagement in the learning process.

In the context of physics learning, particularly in the Carnot cycle, the use of simulation plays a crucial role because it overcomes the limitations of visualizing abstract concepts. Simulations allow students to directly observe the relationships between variables, thus facilitating conceptual understanding while enhancing digital literacy. Overall, the results of this study indicate that simulation-based learning has significant potential in improving students' digital literacy, particularly in the exploratory and operational aspects. However, developing digital literacy holistically requires a more comprehensive learning approach, one that focuses not only on exploration but also on developing evaluation and reflection skills.

To determine students' digital literacy achievement before and after learning using PhySIC-SIM, descriptive statistical analysis was conducted on the students' pretest and posttest results. The results showed that the average pretest score was 13.11 out of a maximum score of 25, representing 52.44%, which indicates that students' initial digital literacy skills were still in the moderate-to-low category. After the implementation of PhySIC-SIM-based learning, the average posttest score increased to 21.63 with an average percentage of 87%, indicating a substantial improvement in students' digital literacy achievement. In addition, the lower standard deviation in the posttest suggests that students' abilities became more homogeneous after the intervention.

To examine the magnitude of improvement in greater detail, N-gain analysis was conducted for each respondent. The N-Gain values ranged from 0.50 to 0.92, with an average N-Gain value of 0.71, which falls into the high category. This finding indicates that the use of PhySIC-SIM was associated with a substantial increase in students' digital literacy skills. Furthermore, the paired sample t-test revealed a significance value of $p < 0.05$, indicating a statistically significant difference between pretest and posttest scores. The effect size analysis using Cohen's d produced a value of 3.16, which indicates a very large practical effect of the intervention on students' digital literacy development. These findings suggest that simulation-based learning using PhySIC-SIM has strong potential to support digital literacy development in thermodynamics learning contexts. However, because this study employed a one-group pretest-posttest design without a control group, the findings should be interpreted carefully as evidence of improvement associated with the intervention rather than definitive causal proof.

The results of this study can be interpreted through the multidimensional framework of digital literacy proposed by Ng, which includes technical, cognitive, and social dimensions. Through PhySIC-SIM, students were not only required to operate digital technology but also to analyze simulation data, interpret thermodynamic processes, communicate findings, and engage in collaborative problem-solving activities. These learning experiences encouraged active interaction with digital environments and promoted meaningful engagement in technology-based learning. From a constructivist perspective, the simulation facilitated active knowledge construction because students learned by exploring variables, observing changes, and interpreting simulation outcomes rather than passively receiving information. This finding supports the view that interactive simulations can create student-centered learning environments that enhance both conceptual understanding and digital competencies.

The findings are consistent with previous studies showing that simulation-based learning can improve student engagement, conceptual understanding, and digital competencies. Studies by Rutten et al., Radianti et al., and Parong and Mayer reported that interactive simulations increase student participation and facilitate exploratory learning processes. Similarly, the present study found that students became more actively engaged in exploring thermodynamic processes through direct interaction with PhySIC-SIM. Furthermore, the findings align with the work of Makransky et al., who demonstrated that exploratory interactions in digital environments strengthen cognitive engagement and support the development of technology-related competencies. However, unlike many previous studies that mainly focused on conceptual achievement or general digital literacy outcomes, this study specifically examined digital literacy development across multiple indicators within the context of thermodynamics learning for prospective physics teachers. Therefore, this study extends previous research by showing that the influence of simulation-based learning differs across dimensions of digital literacy.

The novelty of PhySIC-SIM lies not only in its function as a visualization tool for the Carnot cycle but also in its integration of digital literacy-oriented learning activities within simulation-based physics instruction. Unlike general simulation applications that primarily emphasize conceptual understanding, PhySIC-SIM was intentionally designed to integrate exploratory learning, data interpretation, collaborative discussion, communication of findings, and technology-based problem-solving. In addition, the application was specifically implemented in the context of prospective physics teacher education, making it relevant to the development of pedagogical and technological competencies required in 21st-century education. Thus, the contribution of this study extends beyond merely reporting the use of simulation media and highlights the integration of simulation-based learning with multidimensional digital literacy development.

The indicators of digital literacy used in this study were adapted from multidimensional digital literacy frameworks proposed by Ng and van Laar, which conceptualize digital literacy as consisting of technical, cognitive, and social competencies. Indicators such as understanding basic concepts and configuring operating units represent technical competencies because they involve operational understanding and the ability to use digital tools effectively. Indicators including selecting databases and evaluating validity represent cognitive competencies because they involve information evaluation, critical thinking, and evidence-based decision-making. Meanwhile, indicators such as communicating results, providing feedback, and dividing projects reflect social and collaborative dimensions because they involve interaction, collaboration, and communication in digital environments. Therefore, although several indicators may appear closely related to technical or project-management skills, they were operationalized as dimensions of digital literacy within technology-based learning contexts.

When analyzed based on indicators, the improvement in digital literacy was not evenly distributed across all dimensions. Indicators related to exploratory and operational skills, such as optimizing creativity, configuring operating units, and communicating results, demonstrated higher improvement than evaluative indicators. Table 5 presents the comparison of pretest, posttest, N-Gain, significance, and effect size values for each digital literacy indicator.

Table 5. Improvement of Digital Literacy Based on Indicators

Indicator	Pretest	Posttest	N-Gain	Category	Significance	Effect Size
Understanding basic concepts	Moderate	High	0.69	Medium	Significant	Large
Configuring operating units	Moderate	High	0.78	High	Significant	Large
Optimizing creativity	Moderate	High	0.81	High	Significant	Very Large
Dividing projects	Moderate	High	0.7	High	Significant	Large
Managing revisions	Low	Moderate	0.52	Medium	Less Significant	Medium
Communicating results	Moderate	High	0.79	High	Significant	Very Large
Providing feedback	Moderate	High	0.68	Medium	Significant	Large
Selecting databases	Low	Moderate	0.5	Medium	Less Significant	Medium
Evaluating validity	Moderate	Moderate –High	0.58	Medium	Significant	Medium

The results in Table 5 indicate that PhySIC-SIM was particularly effective in supporting exploratory and operational competencies. Students were able to manipulate thermodynamic variables directly, observe real-time changes in simulation outputs, and discuss findings collaboratively. These learning experiences likely contributed to the enhancement of operational and communication-related digital skills. These findings are consistent with the work of de Jong and van Joolingen, who argued that exploratory simulation environments encourage creativity, experimentation, and active engagement in scientific learning.

In contrast, indicators related to evaluative and reflective digital literacy, such as managing revisions, selecting databases, and evaluating validity, showed relatively lower improvement and weaker significance levels. This finding suggests that higher-order digital literacy skills require more complex cognitive processes and sustained learning experiences than operational competencies. Evaluative literacy involves critical assessment of information sources, reflective thinking, evidence-based reasoning, and systematic revision processes. Such competencies may not develop optimally through simulation interaction alone. This finding supports the study of Spante et al., which reported that technology-based learning environments often improve operational digital skills more effectively than evaluative and reflective competencies.

Several factors may explain why evaluative indicators did not develop optimally. First, the learning activities in PhySIC-SIM emphasized exploration, manipulation, and observation of simulation processes, which naturally support exploratory and operational competencies more strongly than reflective evaluation. Second, students may still have limited experience in critically evaluating digital information sources and revising digital work systematically. Third, evaluative digital literacy requires scaffolding and reflective instructional support beyond simulation interaction itself. Therefore, the findings indicate that future implementations of PhySIC-SIM should integrate additional pedagogical strategies such as guided reflection, structured feedback, inquiry-based assignments, peer review activities, and evidence-analysis tasks to strengthen evaluative and critical digital literacy skills more comprehensively.

From a pedagogical perspective, the findings highlight the importance of integrating interactive simulations into physics teacher education. PhySIC-SIM not only functioned as a visualization tool for abstract thermodynamic concepts but also served as a medium for developing students' digital competencies relevant to 21st-century learning. The integration of exploration, communication, collaboration, and problem-solving activities within simulation-based learning can support more student-centered and inquiry-oriented instructional practices. For prospective physics teachers, such experiences are particularly important because they prepare future educators to integrate educational technology meaningfully into science learning environments. These findings imply that digital literacy should not be taught separately as an isolated technical skill but embedded contextually within subject-specific learning activities.

Despite the positive findings, this study has several limitations. First, the use of a one-group pretest-posttest design without a comparison group limits the ability to conclude that the observed improvements were caused solely by the use of PhySIC-SIM. Other external factors, such as students' prior familiarity with digital technology or classroom interactions, may also have influenced the results. Second, the sample size was relatively small and limited to prospective physics teacher students from a single institution, which restricts the generalizability of the findings. Third, the study focused mainly on short-term digital literacy improvement and did not investigate long-term retention of digital competencies. In addition, the study relied primarily on quantitative data and did not explore students' perceptions or experiences in depth. Therefore, future studies are recommended to employ more rigorous experimental designs involving control groups and larger participant samples. Further research should also investigate how scaffolding strategies, reflective learning activities, and inquiry-based tasks can support evaluative and critical digital literacy competencies more effectively. Qualitative approaches such as interviews, observations, and learning analytics may also provide deeper insights into students' experiences while using PhySIC-SIM and how simulation-based learning contributes to multidimensional digital literacy development in physics education.

CONCLUSION

Based on the research results, it can be concluded that the use of the PhySIC-SIM interactive simulation application on the Carnot cycle material can improve the digital literacy of prospective physics teacher students. This improvement is indicated by an increase in the average score from pretest to posttest, a high N-Gain value, and paired sample t-test results that show significant differences in most indicators. In addition, the very large effect size value indicates that applied learning has a strong influence on improving students' digital literacy. Reviewed based on indicators, the increase in digital literacy did not occur evenly. Indicators related to the exploratory and operational aspects showed a higher increase, while indicators related to the evaluative aspect showed a relatively lower and insignificant increase. This indicates that simulation-based learning is more effective in developing exploratory skills than evaluative skills. Thus, PhySIC-SIM can be used as an alternative learning medium that is effective in improving students' digital literacy. However, to develop digital literacy comprehensively, especially in the evaluative aspect, additional learning strategies that support higher-order thinking skills are needed. Despite the positive findings, this study has several limitations. First, the study employed a one-group pretest-post test design without a comparison group, which limits the ability to attribute improvements exclusively to the PhySIC-SIM intervention. Other external factors, such as prior technological familiarity or classroom interactions, may also have contributed to the observed improvements. Second, the sample size was relatively small and limited to prospective physics teacher students from a single institution, which restricts the generalizability of the findings to broader educational contexts. Third, the study focused primarily on short-term improvements in digital literacy and did not examine the long-term retention of digital competencies. In addition, the study relied mainly on quantitative data, so students' experiences and perceptions regarding the use of PhySIC-SIM were not explored in depth. Therefore, future studies are recommended to employ more rigorous experimental designs involving control groups and larger participant samples to strengthen the validity of the findings. Further research could also investigate the long-term impact of simulation-based learning on digital literacy development and explore how different instructional strategies can support evaluative and reflective dimensions of digital literacy more effectively. In addition, future studies may integrate qualitative approaches, such as interviews or classroom observations, to gain deeper insights into students' learning experiences while using PhySIC-SIM. Such investigations would contribute to a more comprehensive understanding of how interactive simulations can support both conceptual learning and digital competency development in physics education.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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