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Bridging Scientific Literacy and Sustainability Awareness via 7E Inquiry Learning: A Digital Simulation Approach

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Abstract

As global educational standards shift toward addressing environmental crises, integrating sustainability values into science curricula has become imperative. This study develops a 7E inquiry learning cycle model integrated with digital simulations designed to enhance students' scientific literacy, anchored in sustainability awareness and the PISA 2025 framework. Using the Plomp research and development model, the study involved Science Education students selected via purposive sampling. Data were collected through expert validation sheets, scientific literacy tests, and a sustainability awareness questionnaire. The results indicate that the developed model and digital simulation-based learning devices achieved "very high" validity and practicality, with one-to-one (81.96%) and small group (85.45%) evaluations confirming their readiness for classroom implementation. Effectiveness tests revealed that the 7E digital simulation model, sustainability awareness, and their interaction significantly improved students' scientific literacy. The effect size (partial eta squared) demonstrated a robust influence from the learning model (ηp2 = 0.83) and sustainability awareness (ηp2 = 0.74).These findings suggest that bridging inquiry learning with digital tools effectively fosters the dimensions of explaining phenomena and interpreting scientific data within a value-based framework. This research contributes to the discourse on how higher education can cultivate responsible citizenship by embedding sustainability and digital-interactive inquiry as core values in science learning, aligning with the evolving requirements of the PISA 2025 framework.

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Introduction

The escalating complexity of global challenges, such as climate change and biodiversity loss, demands a paradigm shift in science education. In response, scientific literacy has become a central pillar of global educational reforms and a primary indicator of systemic quality within the Programme for International Student Assessment (PISA) frameworks (Ayu et al., 2025; OECD, 2023a). However, Indonesian students consistently encounter difficulties in advancing beyond factual recall toward higher-order scientific reasoning and evidence-based argumentation (OECD, 2018). This discrepancy suggests that scientific literacy should be redefined: it is not merely a cognitive milestone, but a cultural necessity and a value-driven competency required to navigate modern societal challenges

However, the contemporary learning environment in Indonesia remains predominantly characterized by teacher-centered instruction and memorization, restricting the inquiry-based exploration required to develop advanced scientific thinking (Mellyzar et al., 2022; Siswanto et al., 2023). This deficit is deeply embedded in initial teacher training, where pre-service students frequently lack the rigorous professional provisions needed to implement inquiry-driven learning. Notably, a preliminary study conducted at Universitas Negeri Medan confirms these concerns, indicating that prospective science teachers demonstrated competencies merely in the 'sufficient' range (64.5 - 67.4) regarding the evaluation of scientific investigations and data interpretation (Simatupang et al., 2024). Such findings highlight a critical need for a well-structured pedagogical framework to effectively bridge the gap between theoretical understanding and applied inquiry skills.

Concurrently, the United Nations 2030 Agenda and Sustainable Development Goals (SDGs) underscore the imperative for science education to foster the values and attitudes critical to a sustainable future (UNESCO, 2020). Sustainability awareness, as structured by the Sustainability Awareness Framework (SusAF), entails evaluating the interconnected environmental, social, and economic impacts of societal activities (Janssens et al., 2022; Ozis et al., 2022). Despite strong global momentum for Education for Sustainable Development (ESD), its practical implementation in Indonesia is still underrepresented. Empirical evidence from a survey in North Sumatra reveals that 71.9% of science educators have never integrated sustainability-based assessments, demonstrating a significant 'value gap' in contemporary science education (Simatupang et al., 2024).

While inquiry-based learning, particularly the 7E Learning Cycle model, has been recognized for its effectiveness in scaffolding the scientific process (Balta & Sarac, 2016), significant gaps remain in the existing literature regarding the use of technology-enhanced environments. Most research on the 7E model focuses on general achievement without integrating digital simulation as a bridge to visualize complex sustainability phenomena or internationally validated literacy frameworks. Specifically, there is a lack of research that systematically develops a model aligning the 7E cycle with the PISA 2025 framework and SusAF through a digital approach. Moreover, evidence from the field shows that 65.6% of teaching materials are not yet aligned with these emerging global standards (Simatupang et al., 2024), necessitating a new, integrative pedagogical approach. Universities play a crucial role as agents of societal transformation by integrating sustainability into their curricula and academic operations, significantly deepening students' long-term commitment to sustainable behavior. (Dziubaniuk et al., 2024; Khare & Stewart, 2024).

Despite this strong global momentum, sustainability education in Indonesia remains a relatively minor part of the learning strategy, partly due to the lack of interactive media that can simulate real-world environmental impacts. This contrasts with European countries that have developed and implemented comprehensive ESD curriculum frameworks across all levels of education (Fekih Zguir et al., 2021). A survey of junior high school science teachers in North Sumatra found that 71.9% had never conducted a sustainability awareness-based assessment, and nearly 70% admitted to having received no ESD training during pre-service or in-service education (Simatupang et al., 2024).

Given the persistent shortcomings in science education, inquiry-based learning supported by digital simulation has emerged as one of the most consistently recommended approaches for developing scientific literacy. Essentially, inquiry learning positions students as active knowledge builders, engaged in the process of questioning, investigating, and explaining phenomena, rather than simply passively receiving information. A comprehensive bibliometric analysis covering 662 inquiry-based science learning studies published between 2000 and 2021 (Kutlu Abu, 2023), demonstrates that inquiry learning remains the most influential approach in fostering scientific literacy across all levels of education.

Research consistently documents implementation challenges at each phase of the inquiry cycle, particularly in the absence of concrete experimental tools. In the orientation phase, teachers often struggle to help students with diverse backgrounds connect meaningfully to the context of a given problem (Fitzgerald et al., 2019). This finding reminds us not to assume that inquiry automatically produces the desired benefits and highlights the need for a structured framework with systematic scaffolding, which digital simulation can provide by making abstract concepts visible. The 7E Learning Cycle model offers a structured framework that addresses this need. (Balta & Sarac, 2016), in a study conducted in Turkey, found that teachers who implemented the 7E cycle achieved significantly greater student achievement gains than those who used conventional learning. The clarity of the 7E model's pedagogical phases makes it highly appropriate for assisting teachers in scaffolding the inquiry process, especially when mediated by digital tools that simplify complex data interpretation.

The integration of inquiry-based learning with the 7E Learning Cycle model and digital simulation represents a theoretically coherent and practically promising pedagogical synthesis. When aligned with ESD principles and the PISA 2025 framework, this integrative model can help students bridge the gap between scientific inquiry and real-world sustainability challenges, simultaneously developing both scientific competence and social responsibility. It has even been argued that the most profound form of scientific literacy emerges at the intersection of scientific inquiry, digital exploration, and authentic social relevance (Smith & White, 2024).

However, there are significant gaps in the existing literature regarding the synergy of these elements. Research by Matutes and Sangcopan (2022) found that the 7E inquiry model is effective in increasing the interest of prospective science teachers, yet no research has systematically developed and tested a learning model that integrates inquiry-based learning and the 7E Learning Cycle within the PISA 2025 framework, SusAF, and digital simulation simultaneously. Research on the 7E model rarely utilizes digital technology to measure or foster sustainability awareness, and ESD research in science education rarely uses PISA-based digital assessments to measure learning outcomes. Furthermore, most available research has been conducted outside Indonesia, leaving a significant evidence gap for the Indonesian teacher education context. A needs analysis conducted in North Sumatra confirmed these gaps: 65.6% of teachers stated that available materials were not aligned with the PISA 2025 framework, and 71.9% had never participated in a sustainability awareness-based assessment using digital platforms (Simatupang et al., 2024).

This study addresses these gaps by offering an integrated learning model that links inquiry, the 7E learning cycle, PISA 2025-based scientific literacy, and sustainability awareness through a digital simulation approach. The novelty of this research lies in its synthesis of cutting-edge assessment frameworks and digital technology, positioning scientific literacy as the ability to respond contextually to global challenges via virtual experimentation. Broadly, this approach is relevant to global science education trends emphasizing social responsibility and digital transformation. Practically, it provides Indonesian teacher educators with a validated, future-oriented model and digital instruments to foster a new generation of scientifically literate and ethically responsible educators. Based on the problems identified above, this study seeks to address the following research questions:

1. How is the 7E Inquiry Learning model, integrated with the PISA 2025 framework, Sustainability Awareness Framework (SusAF), and Digital Simulation, developed to meet the criteria of validity and practicality for science teacher education?
2. To what extent does the Digital Simulation based 7E inquiry model effectively bridge and improve students' scientific literacy and sustainability awareness?

Method

Research Design

This study employed a Research and Development (R&D) approach using the Plomp development model, which consists of three flexible and iterative phases: (1) preliminary research, (2) prototyping phase, and (3) assessment phase (Plomp & Nieveen, 2013). This model was selected for its systematic yet adaptable nature in educational innovation (Al-Kamzari & Alias, 2025). Within the assessment phase, a quasi-experimental design was integrated to evaluate the model's effectiveness in a real-world classroom setting.

Participants and Sampling

The study involved 61 Science Education students at the State University of Medan. Participants were selected using purposive sampling, ensuring similarity in student characteristics and academic backgrounds to minimize extraneous variables (Hidayati et al., 2020). The sample was divided into an experimental class (utilizing the 7E Inquiry Learning Cycle) and a control class (direct instruction).

Research Instruments and Data Analysis

To ensure the rigor and technical quality of the developed model, several validated instruments were utilized during the research process. First, the validity of the 7E Inquiry Learning Cycle model was evaluated using content and construct validation sheets assessed by three independent experts in science education. The content validation focused on the alignment between objectives and the novelty of the model, while construct validation examined internal consistency, social systems, and instructional impacts. These qualitative assessments were quantified using Aiken's V-index and Borich's Percentage of Agreement (PoA) to ensure objective expert consensus (Tajuddin et al., 2025). Second, students' scientific literacy was measured through a 30-item multiple-choice test meticulously aligned with the PISA 2025 framework. This test covered three core competencies: explaining phenomena scientifically, evaluating scientific designs and interpreting evidence, and utilizing scientific information for decision-making (OECD, 2023b). Statistical analysis confirmed the instrument's high reliability, with a Cronbach Alpha coefficient of 0.841. Finally, students' sustainability awareness was assessed using the Sustainability Awareness Framework (SusAF) questionnaire, which encompasses emotional, behavioral, and practice-based dimensions. This instrument demonstrated excellent validity with an Aiken's V value of 0.92, ensuring that it was highly representative of the sustainability values being investigated.

Procedures and Formative Evaluation

The development of the 7E Inquiry Learning Cycle specifically designed to bridge scientific literacy and sustainability awareness through a digital simulation approach followed a rigorous formative evaluation workflow as proposed by Tessmer (2013), integrated within the broader Plomp development framework (see Figure 1).

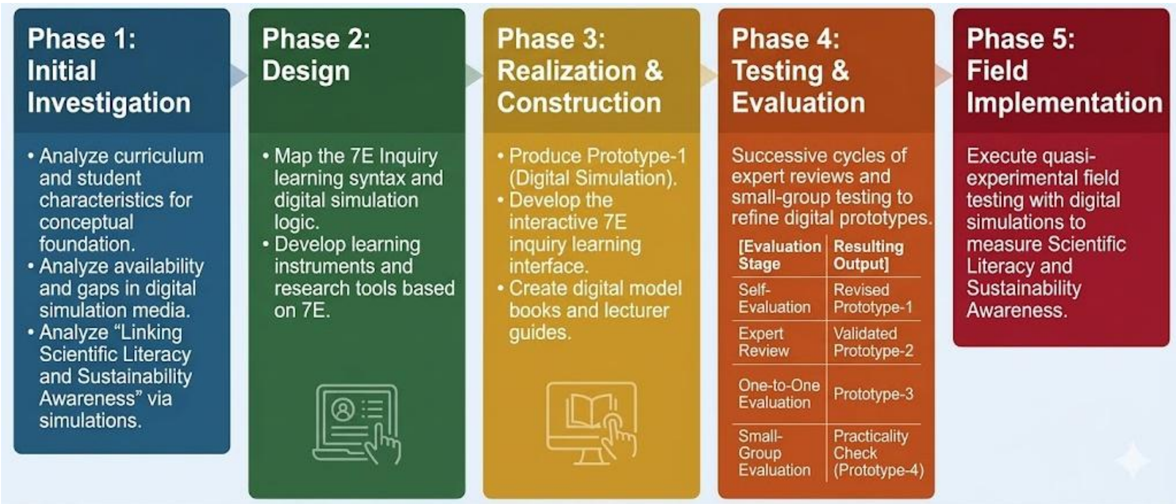

Figure 1. Model Development Flow based of Plomp and Tessmer

The process commenced with the Initial Investigation phase, which involved a comprehensive curriculum analysis, student needs assessment, and an evaluation of student characteristics to establish a solid foundation for the model's design. This was followed by the Design and Construction phase, where the first iteration, Prototype-1, was produced. This prototype included the 7E Inquiry model book, semester lesson plans, and integrated teaching materials. The subsequent Test and Evaluation phase employed a multi-stage formative approach: it began with a self-evaluation, followed by an expert review that resulted in Prototype-2, a one-to-one evaluation leading to Prototype-3, and a small-group evaluation that culminated in a valid Prototype-4. Finally, in the

Implementation phase, the refined model was subjected to a field trial using a quasi-experimental design. To determine the model's impact, its effectiveness on students' scientific literacy, moderated by their levels of sustainability awareness (categorized into high, medium, and low), was statistically analyzed using Two-way ANOVA and Normalized Gain (N-gain) scores. The systematic stages of the model development, integrating the Plomp framework with Tessmer's formative evaluation phases, are visually synthesized in Figure 1. This flowchart illustrates the iterative progression from the initial investigation and prototyping stages to the final assessment phase, ensuring a rigorous and transparent developmental process.

Results

Development of the 7E Inquiry Learning Cycle Model

Through the research and development process, a pedagogically structured 7E Inquiry Learning Cycle model was established to realign scientific literacy with sustainability awareness. By blending the PISA 2025 framework and the Sustainability Awareness Framework (SusAF), this model incorporates digital simulations to optimize the inquiry process. Empirical field data justified this intervention, highlighting that although 96.9% of science educators in North Sumatra endorse inquiry-based recommendations, 71.9% have never deployed the 7E cycle. Additionally, 65.6% reported a lack of instructional resources tailored to PISA 2025 metrics. Consequently, this model was designed to systematically scaffold university students' epistemic knowledge through digital platforms, establishing a robust linkage between scientific competencies and sustainability principles (Dziubaniuk et al., 2024; Filho et al., 2024). Based on these findings, a model was designed to explicitly scaffold students' epistemic knowledge while integrating sustainability values into scientific learning. The finalized model consists of five essential elements: syntax, social system, reaction system, support system, and instructional impact. The structural components are presented in Table 1.

Table 1. Elements of the 7E Learning Cycle Inquiry Learning Model

Model Elements	Component	Description
Syntax	1. Orientation phase (elicit and engage sub-phases) 2. Conceptualization phase (explore and explain sub-phases) 3. Investigation phase (elaborate sub-phase) 4. Conclusion phase (evaluate sub-phase) 5. Discussion phase (extend sub-phase)	Gradual activation of cognitive functions from initial knowledge to transfer into digital based sustainability contexts
Social System	1. Student-centered 2. Lecturers as facilitators and motivators 3. Collaborative inquiry environment 4. Self-regulated learning	Lecturers as facilitators; students as active knowledge constructors within digital simulations.
Reaction System	ZPD-based responsive scaffolding	Adaptive feedback and guided questioning strategies integrated into the learning interface.

Model Elements	Component	Description
Support System	Lecture equipment, learning model books, teaching materials, student worksheets, assessment instruments	Integrated tools aligned with PISA 2025 and sustainability awareness
Instructional & Accompanying Impact	Scientific literacy and sustainability awareness	Measurable improvements in the three PISA 2025 competencies and the three SA dimensions

The model's conceptual novelty is centered within the Extend phase, which functions as a critical cognitive bridge to global sustainability challenges. In this phase, the integrated digital simulation serves as an interactive platform for learner agency, prompting students to deploy scientific literacy when navigating real-world sustainability crises, such as the low-carbon energy transition (Hariyono et al., 2024). This mechanism effectively allows learners to conceptualize and evaluate the long-term environmental ramifications of scientific and technological decisions. To ensure academic rigor and the feasibility of the digital simulation approach, the initial prototype underwent a rigorous validation process. The evaluation focused on the model's ability to bridge scientific literacy with sustainability awareness through 7E-based digital activities. Table 2 summarizes the expert validation results.

Table 2. Validation Results of the 7E Learning Cycle Inquiry Model

Component	Aspect	Average validator value	Aiken's V validity coefficient	Information
Contents	Congruence Between Goals and Needs	4	1.00	Very high
	Supporting Theory of Model Design That Meets Knowledge Novelty	4	1.00	Very high
	Learning Syntax	3.75	0.92	Very high
Construct	Internal Consistency Between Components	3.83	0.94	Very high
	Social System	4	1.00	Very high
	Support System	3.89	0.96	Very high
	Instructional Impact	3.83	0.94	Very high
	Learning Environment	3.83	0.94	Very high
	Assessment and Evaluation	4	1.00	Very high
	Validation percentage		0.97	Very high
	Percentage of Agreement		97%	**Good Reliability**

The data in Table 2 indicate an average Aiken's V coefficient of 0.97, with a Percentage of Agreement (PoA) of 97%, demonstrating very high validity and excellent reliability among experts. These findings confirm the strong internal coherence of the model and its alignment with pedagogical design principles, particularly in its capacity to bridge theoretical science with practical sustainability awareness through a digital simulation framework.

Notably, the components of Goal Congruence and Assessment achieved perfect validity scores (V = 1.00). This confirms that the model effectively integrates international standards, such as the PISA 2025 framework, with local educational needs and digital simulation requirements. The high score in the Social System (1.00) further suggests that the collaborative inquiry environment is well-structured to support students as they navigate complex sustainability scenarios within a digital space**.**

Feasibility of Supporting Learning Devices

Following the validation of the 7E Inquiry model, the supporting instructional devices specifically designed to facilitate the digital simulation approach were assessed for feasibility. These devices serve as the practical infrastructure to bridge students' scientific literacy with sustainability awareness.

Table 3. Feasibility of Learning Devices

Learning Tools	**Main Assessment Aspects**	**Aiken's V validity coefficient**	**Information**
Semester Learning Plan and Lecture Plan	Objective formulation, Material, Language, Time allocation for digital integration	0.94	Very high
Lecturer's Handbook	Instructions for use, 7E model representation, Digital simulation guidance	0.91	Very high
Student teaching materials	Accuracy of content, Depth of concept, Sustainability context, Digital interactivity	0.91	Very high
Student worksheet	Writing approach, Sentence clarity, PISA 2025 indicators, Sustainability scenarios	0.91	Very high

All learning tools achieved high feasibility scores, ranging from 0.91 to 0.94, indicating their readiness for classroom implementation. This high feasibility ensures that the transition between theoretical scientific concepts and digital sustainability simulations is seamless for both lecturers and students. The high feasibility of the Student Worksheets is particularly significant. These worksheets were designed to balance procedural knowledge with epistemic inquiry, a critical factor in improving PISA based scientific literacy scores (Morris, 2025). Furthermore, by incorporating digital simulation tasks into the worksheets, students are encouraged to engage with sustainability challenges in a controlled, interactive environment. The Lecturer's Handbook (V = 0.91) provides the necessary scaffolding for educators to facilitate the 7E cycle effectively, ensuring that the digital simulation approach does not merely become a technical exercise but remains a robust pedagogical tool for bridging scientific literacy and sustainability awareness.

Usability Testing

The model's usability was tested through iterative evaluations to ensure that the digital simulation approach effectively facilitates the bridging of scientific literacy and sustainability awareness. These evaluations focused on student engagement and the practical flow of the 7E Inquiry cycle within a digital context.

Table 4. Results of the One Two One Assessment

Dimensions	Percentage (%)	Revision
Enjoyment of learning components	86.27	-
New learning experiences	85.29	Adding reinforcement to the engagement stage within the digital interface
Ease of understanding components	79.41	Simplification of language and instructions on student worksheets
The attractiveness of the model steps	76.47	Confirmation of transition between 7E stages
Interest in continuing studies	82.35	-

Table 5. Results of the Small Group Assessment

Dimensions	Percentage (%)	Revision
Enjoyment of learning components	87.78	-
New learning experiences	83.89	-
Ease of understanding components	80	-
The attractiveness of the model steps	85.56	Adjustment of time allocation for each digital inquiry stage
Interest in continuing studies	90	-

The one-to-one evaluation (81.96%) confirmed that digital simulations effectively bridged complex scientific data with sustainability scenarios, notably through "New learning experiences" (85.29%). Refinements to instructional language (79.41%) were implemented to further optimize scientific literacy support. Subsequent small group evaluations demonstrated enhanced procedural attractiveness (85.56%) and high academic interest (90%), validating the 7E Inquiry-digital approach as a robust pedagogical bridge for internalizing sustainability awareness and ensuring readiness for field implementation.

Field Trial Results

To evaluate the impact of the developed model, a field trial was conducted. Prior to inferential testing, descriptive statistics were calculated to observe the distribution of scientific literacy scores across both learning models and students' initial ability levels.

Table 6. Descriptive Statistics of Scientific Literacy Scores

Learning Model	Initial Ability	Mean	Std. Deviation	N
7E Inquiry Learning Cycle	High	0.8138	0.0350	8
	Medium	0.6733	0.0345	15
	Low	0.7171	0.0478	7
	Total	**0.7210**	**0.0699**	**30**

Learning Model	Initial Ability	Mean	Std. Deviation	N
Direct Instruction	High	0.6775	0.0361	8
	Medium	0.5493	0.0599	15
	Low	0.3988	0.0348	8
	Total	**0.5435**	**0.1125**	**31**

Students in the experimental group consistently outperformed those in the control group across all initial ability levels. The most notable finding was the substantial improvement among low ability students. Following this, a two-way ANOVA was conducted to confirm the significance of these differences and the interaction between the learning model and sustainability awareness levels. Further analysis using two way ANOVA is shown in Table 7.

Table 7. Summary of Two-Way ANOVA Test Results

Source of Variation	SS	df	F-count	MS	p	η_p^2
Learning Models (7E vs. Direct)	0.514	1	246.310	2.52	<.001	0.83
Sustainability Awareness Level (High/Medium/Low)	0.301	2	77.39	2.52	<.001	0.74
Interaction (Model × Level of Sustainability Awareness)	0.102	2	26.28	2.52	<.001	0.49
Error	0.107	55		0.002		
Total	25.276	61				

The results show significant effects for all variables. The analysis revealed significant effects of the learning model, sustainability awareness level, and the interaction between both variables. The significant interaction effect found in the ANOVA test ($F = 26.28$, $p < .001$, $\eta_p^2 = 0.49$). The practicality analysis revealed that all phases were implemented with very practical ratings: Lecturer mean = 3.81; Student mean = 3.66. Detailed results of the practicality assessment across the instructional phases are presented in Figure 2. As illustrated in Figure 2, the orientation phase received the highest appraisal, while the discussion phase also maintained high practicality.

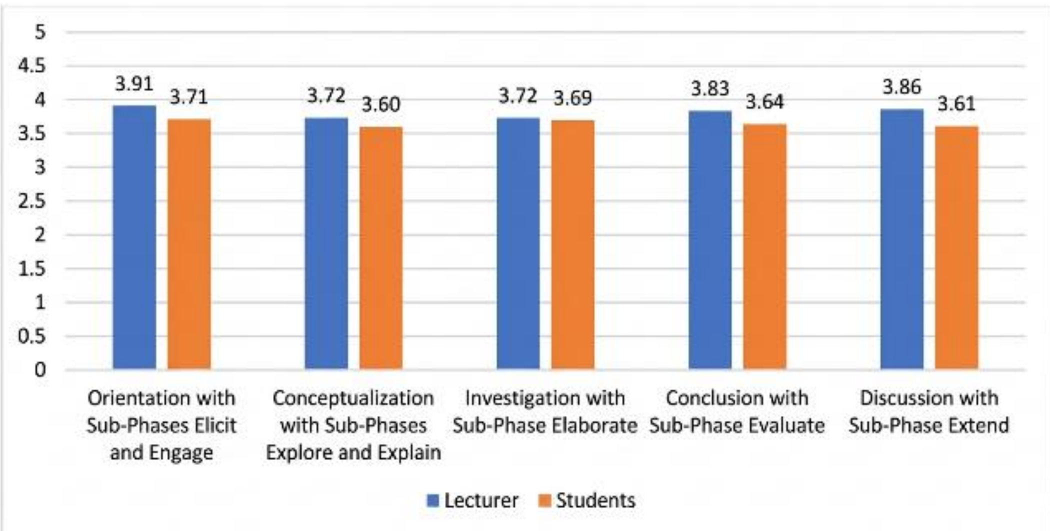

Figure 2. Practicality Scores of the 7E Inquiry Model Implementation from Lecturer and Student Perspectives

Discussion

The findings of this study demonstrate that the developed 7E Inquiry Learning Cycle model, integrated with a digital simulation approach, is not only valid and practical but also exerts a substantial impact on students' scientific literacy, as evidenced by the very large effect size ($\eta p^2 = 0.83$). This result reinforces the growing consensus that inquiry-based learning becomes significantly more effective when structured with digital scaffolding mechanisms rather than implemented as minimally guided discovery (Chen & Chen, 2025; Heppt et al., 2023).

The strong performance of the experimental group aligns with recent empirical studies showing that inquiry learning integrated with digital scaffolding significantly improves scientific literacy outcomes. Unlike conventional instruction, the digital simulation environment provides statistically significant gains in both scientific literacy and overall learning outcomes by allowing students to interact with complex variables in real-time (Wen et al., 2020). Similarly, the use of guided inquiry-based worksheets in this study, which were specifically designed to interface with the digital simulations, enhanced students' literacy and conceptual understanding through structured engagement with scientific problems (Aulia et al., 2018).

A key contribution of this study lies in the digital operationalization of the Extend phase. This phase functions as a virtual space where students transfer scientific understanding into sustainability oriented action through interactive simulations. Unlike previous inquiry models that often isolate sustainability as supplementary content, this digital simulation approach embeds sustainability awareness directly within scientific reasoning by allowing students to visualize the long-term impacts of environmental decisions (Husic, 2024; Widodo & Kaniawati, 2024). The very large effect size for the learning model ($\eta p^2 = 0.83$) indicates that the structured 7E syntax, supported by digital interactivity, accounts for most of the variance in scientific literacy improvement. This confirms that gradual cognitive activation—from eliciting prior knowledge to extending understanding toward real-world contexts via simulation supports meaningful knowledge construction (Ruiz-Martín & Bybee, 2022).

Moreover, the empirical outcomes substantiate that sustainability awareness exerts a profound moderating influence ($\eta p^2 = 0.74$). This demonstrates that the digital simulation approach effectively leverages learners' environmental consciousness to augment their cognitive capacity to interpret complex scientific principles. Students with higher awareness levels achieved superior literacy gains, suggesting that sustainability awareness functions as "cognitive capital" that is further activated when students engage with digital sustainability scenarios (Kuehl et al., 2023; Nguyen et al., 2024).

The significant interaction effect ($\eta p^2 = 0.49$) suggests that the effectiveness of the 7E model is conditional, depending on how the digital simulation aligns with students' initial characteristics. This strengthens the argument that the success of inquiry learning lies in how the digital tools are designed to provide scaffolding within the Zone of Proximal Development (ZPD), enabling students to navigate complex tasks without cognitive overload (Antonio & Prudente, 2023; Yang et al., 2023).

From a practical perspective, the high practicality scores indicate that the digital simulation approach provides a coherent and manageable instructional flow. However, the study identifies salient challenges: the execution of this framework necessitates (1) structured digital planning and (2) baseline student readiness in digital literacy. To mitigate these, prospective endeavors should investigate flipped classroom methodologies to ensure foundational knowledge is acquired prior to engaging in rigorous in-class digital simulations.

In a wider perspective, the convergence of PISA 2025 competencies, 7E inquiry, and digital simulations marks a meaningful progression in science education. This integrated framework not only strengthens cognitive capacities but also cultivates the informed decision-making abilities needed to address complex global issues. Accordingly, this model emerges as a comprehensive, adaptable approach for bridging scientific literacy and sustainability awareness in alignment with international standards.

Conclusion

This study successfully developed and validated an integrated 7E Inquiry Learning Cycle model specifically designed to bridge scientific literacy and sustainability awareness through a digital simulation approach. The findings confirm that the model, along with its supporting digital-based instructional devices, meets the highest standards of validity (Aiken's V = 0.97) and practicality, ensuring its readiness for implementation in science teacher education. Iterative evaluations from one-to-one and small-group trials further reinforce the model's intuitive syntax and its effectiveness in utilizing digital simulations to engage students with complex sustainability-based contexts.

The empirical evidence demonstrates that the 7E Inquiry model, when integrated with a digital framework, serves as a transformative pedagogical tool for enhancing scientific literacy. The model yielded a substantial effect size ($\eta p^2 = 0.83$), indicating a profound impact compared to traditional instruction, particularly in fostering competencies related to explaining phenomena and interpreting scientific evidence within virtual sustainability environments. Furthermore, the significant interaction between the learning model and students' initial sustainability awareness highlights that embedding values into the inquiry process facilitated by digital simulations—acts as a cognitive catalyst, making science learning more contextual, interactive, and purposeful.

Practically, the implementation of this model fosters a holistic view of science, where students utilize digital platforms to analyze problems, evaluate evidence, and simulate responsible actions. However, several constraints were identified: the execution of digital inquiry requires more extensive planning time compared to conventional methods and demands high student readiness in both digital and scientific literacy prior to lectures. Future research should consider integrating a flipped classroom approach to optimize time allocation, allowing students to master foundational concepts before engaging in rigorous in-class digital simulations.

Overall, the integration of scientific inquiry, PISA 2025 competencies, and sustainability awareness via digital simulation provides a robust framework for preparing future-oriented and ethically responsible science educators. The developed model contributes both theoretically and practically to science education innovation by offering a workable, technology-enhanced approach to enhancing scientific literacy in a sustainability-driven educational context.

Recommendations

To optimize the pedagogical efficacy of science education, institutions must transition from traditional, direct instruction toward a digitally enhanced 7E Inquiry Learning Cycle comprising the Elicit, Engage, Explore, Explain, Elaborate, Evaluate, and Extend phases. This instructional model should be dynamically calibrated to support university students across diverse baselines of initial scientific literacy by leveraging digital simulations as adaptive scaffolding mechanisms. Centrally, the integration of the Sustainability Awareness Framework (SusAF) within the 'Extend' phase must be prioritized to serve as a digital cognitive conduit, enabling pre-service teachers to safely project and apply scientific competencies toward resolving complex socio-ecological dilemmas, such as the low-carbon energy transition. Concurrently, curriculum designers should align instructional architecture with PISA 2025 frameworks and deploy validated support systems, including integrated simulation platforms and interactive model books, to effectively mitigate the professional 'value gap' among lecturers. To circumvent institutional schedule constraints, the institutionalization of a flipped classroom methodology is highly recommended; this strategy delegates foundational theoretical acquisition to asynchronous learning, thereby maximizing synchronous class time for intensive, guided digital inquiry. Finally, universities must invest in targeted professional development programs that empower faculty members to facilitate simulation-driven inquiry, ensuring that technology acts as a robust catalyst for both rigorous scientific mastery and systemic environmental responsibility.

Statements and Declarations

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