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Effectiveness of the PISA-DigiPjBL Model in Enhancing Scientific Literacy, Critical Thinking Skills, and Deep Learning of Physics Education Students

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Abstract

This study examines the effectiveness of the PISA-DigiPjBL learning design in enhancing scientific literacy, critical thinking skills, and deep learning among undergraduate Physics Education students. A quasi-experimental study with a non-equivalent control group design was conducted involving 69 students enrolled in a Static Fluids course at Universitas Syiah Kuala, consisting of an experimental group (35 students) and a control group (34 students). The experimental group engaged in PISA-oriented digital project-based learning supported by a virtual laboratory, while the control group implemented conventional project-based learning supported by physical laboratory activities without digital integration. Accordingly, the findings are interpreted as the effect of an integrated PISA-oriented digital project-based learning environment rather than a single instructional component. Scientific literacy and critical thinking skills were measured using validated essay-based tests, while deep learning was assessed through a structured observation sheet capturing students' learning behaviors during instructional activities. Content validity for all instruments was established through expert judgment, and reliability analyses indicated high internal consistency for the tests and excellent inter-rater agreement for the observation instrument. Data were analyzed using normality and homogeneity tests followed by independent sample t-tests. The results show that the experimental group achieved significantly higher gains in scientific literacy and critical thinking skills than the control group ($\alpha = 0.05$), with large effect sizes (Cohen's $d = 1.30$ for scientific literacy and 1.17 for critical thinking). Observational data further indicate that students in the experimental group demonstrated very high levels of deep learning behaviors, characterized by active engagement and collaboration, critical problem solving, creativity and innovation, and real-world application of physics concepts. These findings suggest that the PISA-DigiPjBL learning design is effective in promoting meaningful and deep learning in physics education at the higher education level when PISA-oriented project-based learning is integrated with digital learning environments.

Keywords: PISA-DigiPjBL; scientific literacy; critical thinking; deep learning

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INTRODUCTION

Digital transformation in higher education requires learning strategies that are not only technologically relevant but also capable of fostering essential 21st-century competencies. These competencies include scientific literacy, critical thinking skills, and deep learning (Voogt, 2012; Redecker, 2017). These competencies are fundamental for preparing prospective physics teachers to face the increasing complexity of modern science education, which requires the integration of conceptual understanding, scientific reasoning, and contextual problem-solving abilities (Darling et al., 2020). In physics education, deep conceptual understanding and the ability to apply scientific knowledge in authentic contexts are crucial to developing reflective and professional graduates apable of responding to real-world scientific challenges (Hestenes, 2015; de Jong et al., 2020).

Along with the rapid development of digital technology, Project-Based Learning (PjBL) integrated with digital platforms offers significant potential to enhance the quality of learning processes. PjBL encourages students to actively engage in solving authentic problems, collaborate with peers, and reflect on both the learning process and outcomes (Kokotsaki et al., 2016; Krajcik, 2014). When supported by digital technology, PjBL creates a more interactive, flexible, and cognitively challenging learning environment, which can promote higher-order thinking skills and meaningful learning experiences (Firmansyah, 2023; Hernández et al., 2020; Bond et al., 2021).

Deep learning emphasizes meaningful conceptual understanding, the ability to analyze and solve complex problems, and the transfer of knowledge to new situations (Marton & Säljö, 1976; Biggs, 2011). Learners who engage in deep learning do not merely memorize information but actively construct conceptual connections, evaluate evidence, and apply knowledge reflectively in real-world contexts (Entwistle, 2015; Wenzel et al., 2022). Consequently, learning strategies in higher education should be intentionally designed to promote active, reflective, and contextual cognitive engagement to support deep learning outcomes, particularly in science and physics education where conceptual coherence is critical (Chi, 2014; Freeman et al., 2014).

One promising approach to achieving these objectives is the integration of digital Project-Based Learning with the scientific literacy framework of the Programme for International Student Assessment (PISA). The PISA framework emphasizes individuals' abilities to apply scientific knowledge to explain phenomena, evaluate scientific information, and make evidence-based decisions in everyday life (OECD, 2018). This orientation aligns closely with the goals of physics education, which extend beyond conceptual mastery to include scientific reasoning and contextual problem-solving skills (Lederman et al., 2014; Furtak et al., 2012). Although PISA has traditionally been associated with secondary education assessment, recent studies emphasize its relevance as a scientific literacy framework applicable to higher education, particularly for developing scientific reasoning, evidence-based decision-making, and contextual problem solving among pre-service teachers (Winarno et al., 2023).

Previous studies have demonstrated that PjBL contributes positively to students' critical thinking skills and active engagement in learning. In higher education physics contexts, digital project-based learning has been shown to enhance conceptual understanding and student engagement; however, most studies emphasize cognitive outcomes without integrating structured scientific literacy frameworks such as PISA. PjBL provides opportunities for learners to address complex problems, collaboratively develop solutions, and apply theoretical knowledge in authentic contexts (Thomas, 2000; Tafakur et al., 2023; Umam et al., 2022). In addition, recent research indicates that digitally supported PjBL is effective in enhancing students' creative thinking skills and innovation capacity, while simultaneously supporting the achievement of Sustainable Development Goal 4 (quality education) in higher education (Prahani et al., 2025; UNESCO. 2021). These findings suggest that the integration of PjBL and digital technology has considerable potential to improve science learning outcomes.

However, existing studies generally focus on improving critical or creative thinking skills in isolation and have rarely examined the explicit integration of the PISA scientific literacy framework within digital Project-Based Learning environments, particularly in the context of physics education. Moreover, empirical research investigating the impact of such integrated instructional models on students' deep learning remains limited, even though deep learning is widely recognized as a key indicator of meaningful learning in higher education (Wenzel et al., 2022). This limitation is increasingly problematic, as prospective physics teachers are expected not only to master scientific concepts but also to apply them critically, evaluate evidence, and make informed decisions in authentic and digitally mediated contexts. Therefore, this study addresses this gap by proposing a systematic integration of the PISA scientific literacy framework into a digitally supported Project-Based Learning model, referred to as PISA-DigiPjBL.

The novelty of this study lies in the alignment of scientific literacy processes with digital project-based learning activities to simultaneously foster scientific literacy, critical thinking skills, and deep learning. Accordingly, this study aims to examine the effectiveness of the PISA-DigiPjBL model in enhancing scientific literacy, critical thinking skills, and deep learning among physics education students.

METHOD

Research Design

This study employed a quantitative approach using a quasi-experimental method with a pretest–posttest control group design. This design was selected because it allows for the examination of treatment effectiveness in naturally formed groups that are not randomly assigned but have relatively equivalent initial characteristics (Creswell, 2012). The research aimed to examine the effectiveness of the PISA-DigiPjBL model in promoting deep learning, particularly in terms of scientific literacy and critical thinking skills among physics education students.

Participants (Population and Sample)

The study was conducted at the Physics Education Study Program, Faculty of Teacher Training and Education, Universitas Syiah Kuala, during the odd semester of the 2025/2026 academic year. The participants were undergraduate students enrolled in the same physics education course. The sample was selected using purposive sampling, and two intact classes were designated as the experimental and control groups based on availability, comparable class size, and relatively similar academic characteristics and class sizes. One class (35 students) was assigned as the experimental group, while the other class (34 students) served as the control group.

Research Instruments

All research instruments used in this study including the scientific literacy test, critical thinking skills test, project assessment rubric, and deep learning observation sheet were subjected to validity and reliability evaluation prior to implementation. The instructional materials included PISA-DigiPjBL-based e-modules and digital project-based student worksheets (LKPD) used in the experimental group, as well as printed non-digital project-based worksheets used in the control group. Additional research instruments consisted of scientific literacy tests based on PISA frameworks, critical thinking skills tests, project assessment rubrics, and deep learning observation sheets. All instruments were validated by three experts validators all of whom were lecturers in Universitas Syiah Kuala, with the following areas of expertise: 1) Expert in instructional models and learning design, 2) Expert in educational assessment and evaluation, and 3) Expert in physics (content expert). Besides that, all instruments also tested for reliability prior to implementation.

Scientific literacy and critical thinking skills were assessed using validated indicators adapted from the PISA framework (OECD, 2019; OECD, 2022) and Ennis's critical thinking taxonomy (Ennis, 2011).

Table 1. Instrument Constructs and Validation Design

Instrument	Construct	Indicators / Dimensions	N of Items / Aspects	Item Type	Scoring Scale	Validation Method
Critical Thinking Test	Critical thinking skills *(Ennis, 2011)*	1) Basic clarification	5	Essay	Rubric score 1–3	Expert judgment

Instrument	Construct	Indicators / Dimensions	N of Items / Aspects	Item Type	Scoring Scale	Validation Method
		2) Building basic skills 3) Advanced explanation 4) Assumptions and integration 5) Making inferences				(Content validity)
Scientific Literacy Test	Scientific literacy competencies (*OECD, 2019; 2022*)	1) Explaining scientific phenomena 2) Interpreting scientific data and evidence 3) Applying scientific concepts in new contexts 4) Communicating scientific information 5) Science–technology–society relations	5	Essay	Rubric score 1–3	Expert judgment (Content validity)
Deep Learning Observation Sheet	Deep learning behaviors *(Fullan & Langworthy, 2014)*	1) Active engagement and collaboration 2) Critical thinking and problem solving 3) Creativity and innovation 4) Real-world application of concepts 5) Technology use for exploration and presentation	5	Observation rubric	Scale 1–4	Expert judgment (Content validity)

Table 2. Essay Scoring Rubric for Critical Thinking and Scientific Literacy

Score	Criteria
3	The response is complete, scientifically accurate, logically argued, and clearly explained.
2	The response is generally correct; key concepts are accurate but explanations are incomplete.
1	The response shows partial understanding with incorrect or insufficient explanation.
0	No response or an irrelevant answer.

Overall, the validation and reliability testing results confirm that the instruments used in this study were valid and reliable for measuring scientific literacy, critical thinking skills, and deep learning in the context of PISA-DigiPjBL implementation.

Data Collection

During the preparation stage, instructional materials for both experimental and control groups were developed, followed by expert validation and instrument try-out to ensure validity and reliability. The experimental implementation stage involved the application of the PISA-DigiPjBL model with digital project outputs in the experimental group, while the control group was taught using conventional project-based learning without digital integration. Data collection included pretests and posttests to measure scientific literacy and critical thinking skills, classroom observations, project documentation, and student perception questionnaires. Finally, data analysis was conducted using both quantitative and qualitative approaches, including normality and homogeneity tests, *t*-tests, N-gain analysis, and descriptive analysis of deep learning indicators.

Data Analysis Techniques

Quantitative data analysis was conducted to determine differences and learning effectiveness between groups. Prior to hypothesis testing, normality and homogeneity tests were performed to assess the suitability of parametric analysis. Normality was examined using the Liliefors test, with the hypotheses defined as H_0: data are normally distributed and H_1: data are not normally distributed. A significance value of $p > 0.05$ indicated normal distribution. Learning improvement was measured using the normalized gain (N-gain) formula (Hake, 1998):

$$Ngain(g_i) = \frac{postest\ score - pretest\ score}{\max score - pretest\ score}$$

The N-gain values are presented in the following Table 1.

Table 3. N-Gain Criteria

N-gain score	Criteria
≥ 0,7	High
0,3 ≤ Ngain < 0,7	Moderate
< 0,3	Low

The Learning Effectiveness Index (LEI) was used to describe overall learning effectiveness. LEI was calculated as the average of normalized gain scores from the measured learning outcomes and expressed as a percentage.

$$LEI = \frac{1}{n}\sum_{i=1}^{n} g_i\ x\ 100\%$$

In this study, the normalized gains (g_i) represent students' learning improvements measured using validated essay-based instruments assessing scientific literacy (PISA-based competencies) and critical thinking skills (Ennis framework). The Learning Effectiveness Index (LEI) aggregates these normalized gains to provide an integrated measure of learning effectiveness across these two complementary cognitive outcomes in physics learning. Expressing LEI as a percentage facilitates descriptive comparison of overall learning effectiveness between the experimental and control groups.

If the data met parametric assumptions, a t-test was used to compare pretest and posttest results between the experimental and control groups. For non-normally distributed data, the Mann–Whitney U test was applied. To complement significance testing, effect sizes were calculated using Cohen's d based on t-values and sample sizes to estimate the magnitude of differences between the experimental and control groups. Effect size interpretation followed Cohen's criteria, where d values of 0.8 or higher indicate large effects

Qualitative data served as supporting evidence and were analyzed descriptively. Observation data were quantified to determine the achievement level of deep learning indicators—such as meaning-making, creativity, and problem-solving—using percentage analysis based on the maximum ideal score (Fullan & Langworthy, 2014). The categorization of observation scores followed five levels:

Table 4. Observation Score Categorization Rubric

Percentage of Score from the Maximum Score	Category
≥ 80%	Very high
61% – 79%	High
41% – 60%	Moderate
21% – 40%	Low
≤ 20%	Very low

Furthermore, qualitative data from classroom observations and project documentation were analyzed through data reduction and data display to provide deeper insights into the learning processes occurring during the intervention.

RESULTS AND DISCUSSION

Validity and Reliability Instruments

Following the establishment of the instrument constructs and validation design presented in Table 1, the quality of the research instruments was further examined through content validity and reliability analyses. Content validity was assessed using expert judgment involving three physics education lecturers with expertise in learning models, educational assessment, and physics content. The evaluation focused on the relevance, clarity, and alignment of each item and indicator with the intended constructs.

Subsequently, reliability analyses were conducted to ensure measurement consistency. The reliability of the essay-based critical thinking and scientific literacy tests was evaluated using internal consistency analysis, while the reliability of the deep learning observation sheet was examined through inter-rater reliability analysis. The results of the validity and reliability analyses are summarized in Table 5.

Table 5. Validity and Reliability Results of Research Instruments

Instrument	Number of Validators	Validity Index (CVI)	Validity Category	Reliability Method	Reliability Coefficient	Reliability Category
Critical Thinking Essay Test	3	0.84–0.91	Very High	Cronbach's Alpha	0.82	High
Scientific Literacy Essay Test	3	0.83–0.90	Very High	Cronbach's Alpha	0.80	High
Deep Learning Observation Sheet	3	0.85–0.92	Very High	Inter-rater reliability (ICC)	0.87	Excellent

Table 5 summarizes the validity and reliability results of the instruments. The Content Validity Index (CVI) values ranged from 0.83 to 0.92, indicating very high content validity across all instruments. The reliability analysis revealed high internal consistency for the critical thinking and scientific literacy tests, with Cronbach's alpha coefficients of 0.82 and 0.80, respectively. Furthermore, the deep learning observation sheet demonstrated excellent inter-rater reliability, as indicated by an Intraclass Correlation Coefficient (ICC) of 0.87.

Scientific Literacy and Critical Thinking

The pretest results indicated that the initial levels of scientific literacy and critical thinking skills of students in both the experimental and control groups were relatively equivalent ($p > 0.05$). This finding confirms that the two groups had comparable prior knowledge before the implementation of the learning intervention. After the treatment, posttest results showed improvements in both variables for both groups; however, the magnitude of improvement was notably higher in the experimental group that implemented the PISA-DigiPjBL model.

Table 6. Results of Students' Scientific Literacy and Critical Thinking Tests

Variable	Class	Pretest	Posttest	N-Gain	t	Cohen's d	Interpretation
Scientific literacy	Experiment	61.2	83.6	0.58	5.41	1.30	Large effect
	Control	60.8	74.1	0.34	–	–	–
Critical thinking	Experiment	58.9	80.4	0.55	4.87	1.17	Large effect
	Control	59.3	72.2	0.32	–	–	–

In addition to statistical significance, effect size analysis was conducted to determine the magnitude of the intervention effect. The results indicate a large effect of the PISA-DigiPjBL model on students' scientific literacy (Cohen's d = 1.30) and critical thinking skills (d = 1.17). These values exceed the threshold for large effects, suggesting that the observed differences are not only statistically significant but also educationally meaningful.

As presented in Table 3, the experimental group achieved higher gain scores in scientific literacy (0.58) and critical thinking skills (0.55) compared to the control group (0.34 and 0.32, respectively). Independent sample *t*-test analysis revealed that the calculated *t* values exceeded the critical *t* value ($t_{value} > t_{table}$, $\alpha = 0.05$), indicating statistically significant differences between the experimental and control groups for both variables.

Normality testing using the Liliefors method showed that all data sets were normally distributed ($L_{value} < L_{table}$), while homogeneity testing confirmed equal variances between groups ($F_{value} < F_{table}$). These results support the appropriateness of applying parametric statistical tests to compare learning outcomes between groups. In addition to statistical significance, the observed differences indicate that the PISA-DigiPjBL model had a meaningful impact on students' learning outcomes, although further effect size analysis is recommended to provide a more comprehensive interpretation of practical significance.

Figure 1. presents the Learning Effectiveness Index (LEI) of the experimental and control classes, based on normalized gains of scientific literacy and critical thinking skills. Students taught using the PISA-DigiPjBL model experienced a substantially higher relative improvement compared to those in the conventional project-based learning class. Figure 1 shows that the experimental group demonstrated a higher percentage increase in both scientific literacy and critical thinking skills, indicating a faster learning progression facilitated by the PISA-DigiPjBL model. Moreover, contemporary research highlights that improvements in scientific literacy are closely associated with gains in higher-order thinking skills, suggesting that composite indices like LEI provide a more comprehensive representation of learning outcomes than single-measure analyses (Schwichow et al., 2022).

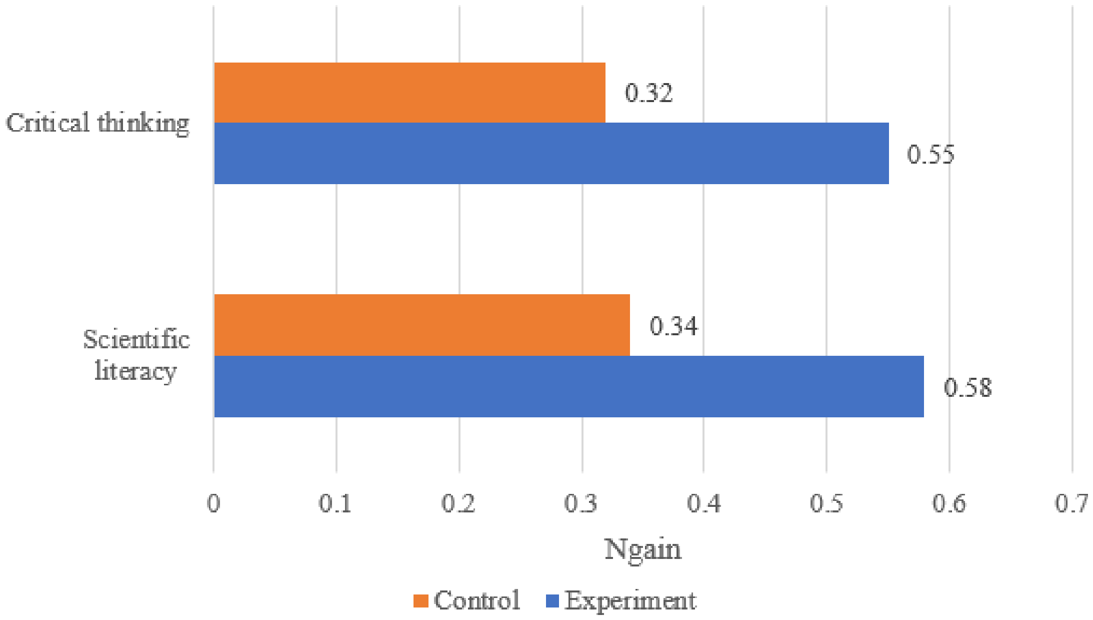

Figure 1. Percentage increase of students' scientific literacy and critical thinking skills in the experimental and control classes

The improvement in scientific literacy among students in the experimental group reflects the effectiveness of integrating PISA-based contexts into physics learning. Students demonstrated enhanced abilities to interpret data, explain scientific phenomena, and evaluate solutions based on scientific evidence—competencies that are emphasized in the PISA 2022 results and the PISA 2025 science framework (OECD, 2023; Bybee, 2018). These competencies align with recent findings showing that scientific literacy development is strongly influenced by contextual and evidence-based learning experiences.

For example, students were better able to connect concepts such as hydrostatic pressure, buoyant force, and Pascal's law with real-life applications, including dam wall pressure, hydraulic systems, and pressure-related phenomena. This finding is consistent with recent studies reporting that PISA-aligned contextual learning significantly enhances students' scientific literacy, particularly in interpreting real-world phenomena and applying scientific reasoning (Ayu et al., 2025; Putri et al., 2025). Furthermore, project-based learning has been shown to strengthen scientific literacy through active engagement and contextual problem-solving processes (Alfiah et al., 2025).

Similar patterns were observed in critical thinking skills. Students in the experimental group demonstrated stronger abilities to identify assumptions, evaluate arguments, and construct logical explanations based on evidence generated through digital simulations. The critical thinking test employed in this study was designed to assess higher-order cognitive processes, including analysis, evaluation, and reasoning; therefore, the observed gains reflect students' engagement in evidence-based reasoning rather than surface-level recall. These findings support previous research indicating that PISA-oriented learning environments effectively promote higher-order thinking skills in science education.

Deep Learning Observation

To ensure data credibility, deep learning outcomes were examined through triangulation of classroom observations, project documentation, and analysis of students' reflective and creative project outputs. Deep learning was observed by three obsevers and using three main indicators: conceptual reflection, conceptual elaboration and integration, and creative application.

Table 7. Average Observation Scores of Students' Deep Learning

Deep Learning Aspect	Control Class	Experimental Class	Category
Active Engagement and Collaboration	72.5	87.3	Very high
Critical Thinking and Problem Solving	70.8	85.9	Very high
Creativity and Innovation	69.1	88.4	Very high
Real-World Application of Concepts	70.8	87.2	Very high
Average	**70.8**	**87.2**	*Very high*

As shown in Table 7, students in the experimental group consistently achieved higher scores across all deep learning indicators compared to those in the control group. The experimental group obtained an overall average score of 87.2, categorized as very high, while the control group achieved an average score of 70.8. This statistically superior performance indicates that the PISA-DigiPjBL model effectively facilitated deeper cognitive engagement by enabling students to integrate conceptual understanding with contextual problem-solving. Similar findings have been reported in recent studies, which emphasize that deep learning is more likely to emerge when students actively construct knowledge through authentic, technology-supported learning tasks rather than relying on procedural or surface-level learning approaches (Howard et al., 2021; Zhao, 2022).

Classroom observations further revealed that students in the experimental group were actively engaged in conceptual reflection and knowledge integration processes. Students frequently connected theoretical physics concepts with results obtained from digital simulations, such as PhET-based experiments and Canva-supported visual representations, and translated their understanding into innovative digital project outputs, including AI-assisted experimental videos and interactive physics infographics. These activities encouraged students to move beyond procedural understanding toward meaningful conceptual engagement, which is a key characteristic of deep learning in higher education contexts (Karakas, 2021).

Qualitative findings reinforced the quantitative results. In terms of conceptual reflection, students were able to explain the relationship between pressure and buoyant force using real-life phenomena, such as submarine buoyancy and pressure measurement devices. Regarding conceptual elaboration, students successfully integrated physics theories with digital experimental data by interpreting graphs and simulation outputs. For creative application, students utilized various digital platforms (e.g., Canva, CapCut, and AI-based presentation tools) to present project results in meaningful and contextually relevant formats. These findings are consistent with recent evidence showing that digitally supported project-based learning environments promote deeper conceptual processing, higher-order thinking, and sustained cognitive engagement when learning activities are situated in authentic problem contexts (Hwang et al., 2023).

The robustness of the findings is further supported by the use of validated and reliable instruments, including strong inter-rater agreement for observational and project-based assessments, ensuring the credibility of reported deep learning outcomes. The findings of this study indicate that the PISA-DigiPjBL model not only improves students' cognitive learning outcomes but also strengthens meaningful learning processes characterized by deep learning. The significant improvements in scientific literacy, critical thinking skills, and deep learning can be explained through three interrelated aspects: (1) the integration of PISA-based contextual learning, (2) the characteristics of digital project-based learning, and (3) reflective learning processes embedded within project activities.

Integration of PISA Contexts in Physics Learning

The PISA-DigiPjBL model situates students in problem-solving contexts that closely resemble real-world situations, shifting learning from formula memorization toward data interpretation, evidence evaluation, and scientific decision-making. The use of authentic PISA contexts such as blood pressure analysis, buoyant force applications, and hydraulic systems enabled students to meaningfully relate static fluid concepts to everyday experiences. This result aligns with contemporary perspectives emphasizing that scientific literacy develops optimally when learners engage with relevant and authentic scientific contexts (OECD, 2023; OECD, 2024).

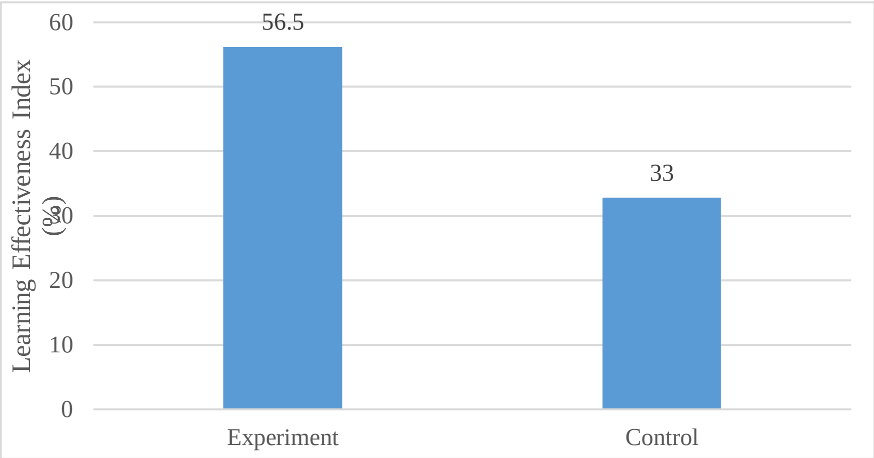

Figure 2. Learning Effectiveness Index (LEI) of the PISA-DigiPjBL model compared to conventional project-based learning

Figure 2 illustrates the Learning Effectiveness Index (LEI) expressed in percentage form, which represents a composite measure derived from the normalized gains of scientific literacy and critical thinking skills. The experimental class achieved a higher LEI (56.5%) compared to the control class (33%) indicating that the PISA-DigiPjBL model was more effective in promoting overall learning outcomes than conventional project-based learning.

The higher LEI obtained by the experimental group suggests that the integration of PISA-oriented contexts within a digitally supported project-based learning environment facilitates balanced and integrated cognitive development.

Moreover, the moderate-to-high LEI percentage observed in the experimental group reflects the contribution of digital project-based learning to deep and meaningful learning processes. Miller and Krajcik (2019) argue that project-based learning promotes deep learning when students are required to integrate concepts, analyze evidence, and apply knowledge to authentic problems. When supported by digital tools, project-based learning further enhances students' opportunities to visualize data, test hypotheses, and reflect on their understanding, thereby strengthening cognitive engagement (Wenzel et al., 2022).

In contrast, the lower LEI in the control group indicates that conventional project-based learning, although beneficial, may be less effective in fostering integrated learning outcomes when digital scaffolding and explicit scientific literacy frameworks are not systematically incorporated. This finding is consistent with Huda (2024), who emphasize that deep learning emerges when pedagogy, technology, and learning goals are coherently aligned. Without such alignment, learning improvements tend to remain fragmented and less sustainable.

Overall, the LEI comparison presented in Figure 2 reinforces the argument that the effectiveness of the PISA-DigiPjBL model lies in its ability to integrate digital technology, PISA scientific competencies, and project-based learning into a coherent instructional framework. This integration supports meaningful and deep learning experiences that are essential for preparing physics education students to address complex scientific and educational challenges in the 21st century.

The substantial increase in scientific literacy scores among students in the experimental group further confirms the effectiveness of contextualized learning in enhancing conceptual understanding. These findings are consistent with recent studies demonstrating that PISA-aligned instructional approaches significantly improve students' data interpretation and scientific reasoning skills (Ayu et al., 2025; Putri et al., 2025).

Enhancement of Critical Thinking through Digital Project-Based Learning

The higher gain in critical thinking skills observed in the experimental group, as reflected by the large effect size and higher N-gain scores, indicates that digital Project-Based Learning creates learning conditions that effectively support higher-order cognitive development. Through the PISA-DigiPjBL model, students engaged in identifying authentic problems, designing investigations, and interpreting simulation-based evidence using digital tools. Such activities are consistent with recent findings showing that digitally supported PjBL environments significantly enhance critical thinking by immersing students in inquiry-driven and evidence-based learning processes (Bond et al., 2023; Hafizah et al., 2024).

Critical thinking gains were strengthened because students were positioned as active designers and evaluators of project solutions rather than passive followers of predetermined procedures. This learner-centered approach encourages students to justify decisions, evaluate alternative explanations, and reflect on the validity of evidence—key components of critical thinking emphasized in recent PISA-oriented and scientific literacy studies (OECD, 2019; Winarno et al., 2023). Empirical evidence from recent Scopus-indexed studies indicates that when project-based learning is explicitly aligned with scientific literacy processes, students demonstrate significantly higher critical thinking performance compared to conventional instruction, as reflected in higher post-test scores, N-gain values, and effect sizes (Santos et al., 2024; Wenzel et al., 2022). These findings support the statistical results of the present study and confirm the effectiveness of the PISA-DigiPjBL model in fostering critical thinking through meaningful, data-driven, and contextually grounded learning experiences.

Deep Learning as an Outcome of Meaningful Learning

A key contribution of this study is the significant improvement observed in deep learning indicators, particularly in conceptual reflection and creative application. Students demonstrated the ability to integrate static fluid concepts with real-life phenomena and to produce digital artifacts that reflected deep conceptual understanding. According to recent studies, deep learning occurs when students are able to elaborate concepts, integrate new knowledge with prior experiences, and apply understanding in novel contexts supported by digital learning environments (Hanifah et al., 2025; Lee et al., 2024). These characteristics were evident in students' digital projects, which visually and interactively explained physical phenomena such as fluid pressure and hydraulic systems. The high average deep learning score (87.2) indicates that students engaged in analysis, reflection, and creativity rather than surface-level learning.

Furthermore, active involvement in digital projects fostered students' sense of agency and ownership over the learning process, contributing to intrinsic motivation and sustained engagement. This finding supports previous research highlighting the effectiveness of digital learning resources, including e-modules and project-based activities, in enhancing scientific literacy and meaningful learning in physics education (Susanti & Syam, 2024; Hanifah et al., 2025).

These findings confirm the novelty of this study, which lies in the explicit integration of the PISA 2025 science framework within a digitally supported project-based learning model (PISA-DigiPjBL). While previous studies have examined PISA-based learning or digital project-based learning independently, this study demonstrates that their systematic integration can simultaneously enhance scientific literacy, critical thinking skills, and deep learning among physics education students at the higher education level, particularly in the context of physics teacher education.

CONCLUSION

This study demonstrates that the PISA-DigiPjBL model is effective in enhancing scientific literacy, critical thinking skills, and deep learning among physics education students. Students who participated in learning activities that integrated PISA-based real-world contexts with digitally supported project-based learning showed significantly higher learning gains compared to those who experienced conventional project-based learning. The model enabled students to actively engage in interpreting data, evaluating scientific evidence, and applying physics concepts to authentic problems, which are core competencies emphasized in the PISA 2025 science framework. Furthermore, the PISA-DigiPjBL model facilitated meaningful learning processes by promoting deep conceptual reflection, conceptual integration, and creative application through digital projects. Students demonstrated improved abilities to connect theoretical knowledge with real-life phenomena and to communicate scientific ideas using digital media. These findings indicate that the integration of PISA-oriented contexts and digital project-based learning not only strengthens cognitive learning outcomes but also supports the development of deep learning essential for preparing future physics teachers.

Overall, this study provides empirical evidence that the systematic integration of PISA 2025 science competencies into digital project-based learning offers a promising instructional model for higher education, particularly in physics teacher education programs. Future research is recommended to examine the long-term impact of the PISA-DigiPjBL model and to explore its implementation across different science disciplines and educational contexts.

RECOMMENDATION

Based on the findings of this study, it is recommended that the PISA-DigiPjBL model be implemented more widely in physics teacher education programs to support the development of scientific literacy, critical thinking skills, and deep learning. Lecturers are encouraged to integrate authentic PISA-based contexts and digital project activities into physics instruction to promote meaningful and contextual learning experiences. Future research should explore the long-term effects of the PISA-DigiPjBL model on students' professional competencies, as well as its applicability across different science disciplines, educational levels, and learning environments. Additionally, further studies may incorporate qualitative approaches or learning analytics to gain deeper insights into students' cognitive and metacognitive processes during digital project-based learning.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mawarni Saputri	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Musdar		✓				✓		✓	✓	✓	✓	✓		
Fadiya Haya	✓		✓	✓			✓			✓	✓		✓	✓

C	:	**C**onceptualization	I	:	**I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	:	**R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	:	**D**ata Curation	P	:	**P**roject administration
Va	:	**Va**lidation	O	:	Writing - **O**riginal Draft	Fu	:	**Fu**nding acquisition
Fo	:	**Fo**rmal analysis	E	:	Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflict of interest related to the research, authorship, or publication of this article.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

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