

NANOTECHNOLOGY-BASED HYBRID PBL–STEAM MODEL TO IMPROVE SCIENTIFIC LITERACY AND HIGHER-ORDER THINKING SKILLS IN INTRODUCTORY SOLID-STATE PHYSICS

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Abstract

The low level of students' scientific literacy and Higher Order Thinking Skills (HOTS) in physics learning has become a crucial issue in 21st-century science education, particularly in responding to the rapid advancement of emerging technologies such as nanotechnology; global education reports indicate that science learning is still dominated by conceptual approaches that lack integration with problem-solving and real technological contexts. Within the broader theoretical landscape of science education, problem-based learning (PBL), STEAM (Science, Technology, Engineering, Arts, and Mathematics) integration, and deep learning-oriented pedagogy are recognized as powerful frameworks to enhance scientific literacy and higher-order thinking through constructive, contextual, and interdisciplinary learning environments. Based on this perspective, this study aims to examine the effectiveness of a Hybrid PBL–STEAM Model Oriented toward Deep Learning Based on Nanotechnology in improving students' scientific literacy and HOTS in an introductory solid-state physics course. The study employed a quasi-experimental design using a mixed-method approach, involving undergraduate physics education students as the unit of analysis. Data were collected through scientific literacy tests, HOTS assessment instruments, classroom observations, and documentation. Data analysis was conducted using descriptive and inferential statistics to measure learning improvement, complemented by qualitative analysis to explore the learning processes. The findings indicate that the implementation of the proposed learning model significantly improves students' scientific literacy and higher-order thinking skills compared to conventional instruction, as reflected by higher N-Gain scores and increased student engagement in nanotechnology-based problem-solving activities.

Keywords: *Nanotechnology, Problem-Based Learning, STEAM Education, Scientific Literacy, Higher-Order Thinking Skills, Solid-State Physics*

INTRODUCTION

The development of the Industrial Revolution 4.0 and the transition toward Society 5.0 have significantly transformed the landscape of higher education. University students are no longer expected merely to master theoretical concepts; they are also required to possess scientific literacy and Higher Order Thinking Skills (HOTS) to adapt effectively to a knowledge-based society. The *Programme for International Student Assessment* (PISA) report indicates that scientific literacy achievement continues to face serious challenges, particularly in the areas of scientific reasoning and data-driven problem-solving (OECD, 2023). In the context of science education in higher education, especially in the *Introduction to Solid State Physics* course, students often encounter difficulties in understanding abstract concepts such as crystal structures, energy bands, and the electrical properties of materials due to their

microscopic and mathematical nature. This condition highlights a gap between the competencies demanded in the 21st century and instructional practices that remain predominantly lecture-oriented. Therefore, there is a need for innovative learning models that are more contextual, integrative, and capable of fostering deeper cognitive engagement.

Several studies conducted over the past five years have demonstrated that the *Problem-Based Learning* (PBL) approach is effective in improving students' problem-solving and critical-thinking skills in economics education (Astuti & Purnamasari, 2025), while the STEAM approach is capable of integrating science, technology, engineering, arts, and mathematics to foster creativity and innovation (Yim et al., 2025). On the other hand, the *deep learning pedagogy* approach has been shown to promote more meaningful and reflective knowledge construction in learning (Chen & Singh, 2024). Furthermore, *Deep Learning* as a learning approach emphasizes profound understanding, critical thinking, creativity, and the ability to apply knowledge in real-world situations (S. Nurhasanah et al., 2025). The integration of nanotechnology into learning has also been found to enhance the relevance of concepts and increase students' learning motivation (Khamhaengpol et al., 2021). However, these studies remain largely partial in nature and have not comprehensively integrated Hybrid PBL–STEAM, *deep learning* orientation, and nanotechnology contexts within a single unified instructional design, particularly in solid-state physics courses. In addition, simultaneous measurement of their impact on students' scientific literacy and Higher Order Thinking Skills (HOTS) remains limited. Therefore, a research gap exists that provides an opportunity for the development of a more systematic and empirically grounded integrative learning model.

Based on this gap, the present study aims to develop and examine the effectiveness of a Nanotechnology-Based Hybrid PBL–STEAM Model Oriented toward *Deep Learning* in enhancing students' scientific literacy and Higher Order Thinking Skills in the *Introduction to Solid State Physics* course. Specifically, this study addresses the following research questions: (1) Does the implementation of the proposed model significantly improve students' scientific literacy compared to conventional instruction? (2) Does the model significantly enhance students' Higher Order Thinking Skills (HOTS)? (3) What is the magnitude of the model's effect (*effect size*) on these two learning outcome variables?

Literature Review

This study argues that the integration of Hybrid PBL–STEAM with a *deep learning* orientation and a nanotechnology context can create a more contextual, collaborative, reflective, and authentically problem-based learning environment. This model not only strengthens students' conceptual understanding of solid-state physics but also promotes the development of analytical, evaluative, and creative thinking skills that constitute the core of Higher Order Thinking Skills (HOTS).

The contribution of this study lies in the development of an integrative learning model that combines four key components—PBL, STEAM, *deep learning pedagogy*, and nanotechnology—within a single conceptual framework that is empirically tested. Theoretically, this research enriches the field of science pedagogy through a multidisciplinary integration approach. Practically, the findings of this study may serve as a foundation for the development of curricula and innovative instructional strategies in higher science education that are aligned with the demands of the 21st century.

In the past five years, research in science education has shown a significant shift toward integrative and student-centered learning approaches aimed at strengthening 21st-century competencies, particularly scientific literacy and *Higher Order Thinking Skills* (HOTS). Several international reports have emphasized that scientific literacy encompasses the ability to understand scientific concepts, interpret scientific data, and make evidence-based decisions within social and technological contexts (OECD, 2023). Recent studies have also highlighted the importance of deep cognitive engagement and contextualized learning in addressing the

limitations of traditional lecture-based instruction (Baihaqi et al., 2025; Budi Utomo & Joko Prayitno, 2025). In general, three major trends have emerged in the literature: (1) the implementation of *Problem-Based Learning* (PBL) to enhance analytical reasoning; (2) the integration of the STEAM approach to strengthen interdisciplinary learning; and (3) the contextualization of abstract scientific concepts through nanotechnology. Nevertheless, the integration of these three approaches into a single comprehensive learning model has rarely been investigated empirically, particularly within the context of solid-state physics.

The first trend focuses on the implementation of *Problem-Based Learning* (PBL) as a strategy for enhancing critical thinking and complex problem-solving skills. Research indicates that PBL encourages students to actively construct knowledge through the investigation of authentic problems and collaborative discussions (Asbar et al., 2025). Further studies have found that PBL contributes significantly to improvements in conceptual understanding and metacognitive skills in higher education (Gabut et al., 2025). In the context of physics education, PBL has been shown to help students understand abstract concepts through the resolution of contextualized problems (Maula et al., 2024; Rumbaru & Widiyasari, 2025). However, most PBL implementations remain monodisciplinary in nature and have not been systematically integrated with interdisciplinary approaches such as STEAM or with an explicit *deep learning* orientation.

The second trend emphasizes the importance of the STEAM (*Science, Technology, Engineering, Arts, and Mathematics*) approach in fostering creativity and innovation through interdisciplinary integration. STEAM enables students to connect scientific concepts with technological applications and engineering design, making learning more contextualized and applicable to real-world situations (Yim et al., 2025). Recent studies have shown that STEAM-based learning enhances students' motivation, collaboration, and creative thinking skills (Khamhaengpol et al., 2021). However, much of the existing STEAM research places greater emphasis on the creative outcomes of products rather than on the depth of conceptual understanding or scientific literacy as a multidimensional construct. Furthermore, the integration of STEAM with the PBL model within a structured instructional framework remains limited in the literature.

The third trend is related to the contextualization of learning through nanotechnology and the implementation of a *deep learning pedagogy* approach. Nanotechnology provides an authentic context for understanding solid-state physics concepts, such as crystal structures, energy bands, and material properties at the nanoscale (Panatarni et al., 2025; Yıldız et al., 2025). The integration of nanotechnology into physics education has been reported to enhance the relevance of learning and increase students' interest and motivation (Affandy, 2020). Meanwhile, the *deep learning* approach emphasizes meaning-making, critical reflection, and the ability to transfer concepts to new situations (N. Nurhasanah et al., 2024; S. Nurhasanah et al., 2025). The integration of creative pedagogy into PBL has been shown to significantly improve higher-order thinking skills among science students, which is highly relevant to the development of HOTS (Affandy et al., 2024). Although both approaches are promising, nanotechnology-based learning often remains focused on content delivery, while the *deep learning* approach is more frequently discussed at the conceptual level without direct empirical integration into discipline-specific instructional designs.

Although previous studies have made important contributions, several limitations remain. First, most studies have examined PBL, STEAM, or nanotechnology separately, resulting in the absence of a comprehensive integrative learning model. Second, learning outcomes are often measured using only a single variable, such as creativity or conceptual understanding, without simultaneously assessing scientific literacy and HOTS. Third, research specifically investigating learning in solid-state physics courses remains limited, despite the field's high level of conceptual complexity. Fourth, the theoretical relationship between the

deep learning approach and standardized cognitive outcome measures has not yet been fully elaborated empirically. These limitations highlight the need for research that integrates pedagogical innovation with comprehensive quantitative evaluation.

Based on these gaps, this study proposes an integrative learning model that combines Hybrid PBL–STEAM, a *deep learning* orientation, and nanotechnology contextualization within the *Introduction to Solid State Physics* course. Unlike previous studies that have examined these components separately, this research positions all four elements within a single unified conceptual framework and empirically investigates their impact on students' scientific literacy and Higher Order Thinking Skills (HOTS). The distinctiveness of this study lies in its integration of interdisciplinary pedagogy, modern nanotechnology contexts, and quantitative evaluation based on *effect size* and *N-gain* analyses, thereby providing both theoretical and practical contributions to the reform of science education in higher education

2. METHODS.

1. Research Design

This study employed a quantitative approach using a pre-experimental design, specifically a one-group pretest–posttest design. This design was used to measure changes in students' abilities before and after the implementation of the Nanotechnology-Based Hybrid PBL–STEAM Model Oriented toward Deep Learning in the *Introduction to Solid State Physics* course. The formula for the one-group pretest–posttest research design used in this study, according to Sugiyono (2018), is as follows:

Table 1. One-Group Pretest–Posttest Design Formula

Group	Pre-test	Treatment	Post-test
Experiment	O_1	X	O_2

Where:

O_1 = Pretest

O_2 = Posttest

X = Treatment (the group receiving the implementation of the Nanotechnology-Based Hybrid PBL–STEAM Model Oriented toward *Deep Learning* in the *Introduction to Solid State Physics* course).

In this design, students were first administered a pretest to determine their initial levels of scientific literacy and Higher Order Thinking Skills (HOTS). They then participated in the learning process using the developed instructional model, followed by a posttest to measure improvements in their learning outcomes (Creswell, 2014). The following figure illustrates the research workflow to be carried out:

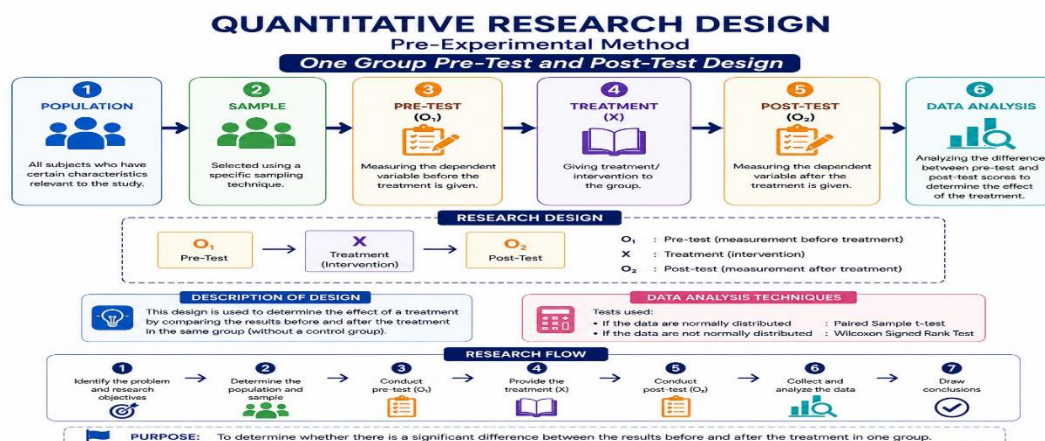


Figure 1. illustrates the research workflow to be carried out

2. Unit of Analysis

The unit of analysis in this study was undergraduate students of the Physics Education Study Program who were enrolled in the *Introduction to Solid State Physics* course during the current semester. The sampling technique employed was purposive sampling, based on the consideration that the selected class participated in the learning process using the instructional model developed in this study.

3. Types of Data

The research data consisted of quantitative data and supporting qualitative data. The quantitative data included students' pretest and posttest scores on scientific literacy and Higher Order Thinking Skills (HOTS). Scientific literacy was measured using a test based on indicators of conceptual understanding, scientific data interpretation, and the application of concepts within nanotechnology contexts. HOTS was measured through essay questions designed to assess students' abilities in analysis, evaluation, and creation according to the revised Bloom's Taxonomy (Anderson & Krathwohl, 2001). The supporting data consisted of students' responses to the implementation of the learning model, which were collected through a five-point Likert-scale questionnaire. In addition, instructional documents such as the Semester Learning Plan (RPS) and project worksheets were analyzed to ensure the fidelity and appropriateness of the model implementation.

4. Data Collection Technique

Data collection was conducted in several stages. First, a pretest was administered to both groups to measure their initial levels of scientific literacy and Higher-Order Thinking Skills (HOTS). Second, the Nanotechnology-Based Deep Learning-Oriented Hybrid PBL–STEAM Model was implemented over eight meetings in the experimental group, while the control group received conventional instruction. Third, a posttest was administered to measure the improvement in learning outcomes.

The test instruments underwent content validity testing by experts in physics education and reliability testing using Cronbach's Alpha coefficient, with a criterion of ≥ 0.70 indicating that the instrument was reliable (Hair et al., 2022). The results of the validity and reliability tests of the research instruments are presented in Table 2 below.

Table 2. Validity and Reliability of the Research Instruments

Instrument	Number of item	Validity (r-count)	criteria	Reliability (Cronbach Alpha)	Interpretation
Science Literacy test	15	0,52 – 0,78	Valid	0,86	Highly Reliable
HOTS test	10	0,50 – 0,75	Valid	0,83	Highly Reliable
Student response questionnaire	12	0,55 – 0,80	Valid	0,88	Highly Reliable

In addition, science literacy was measured using the indicators presented in Table 3 below:

Table 3. Indicators of Science Literacy Measured

No	Literacy Science Indicator	Description
1	Explaining scientific phenomena:	Students are able to explain solid-state physics concepts related to nanotechnology phenomena.
2	Designing and evaluating scientific inquiries:	Students are able to design solutions based on physics concepts for given problems.

3	Interpreting scientific data and evidence:	Students are able to design solutions based on physics concepts for a given problem.
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These indicators were developed based on the scientific literacy framework of the OECD (2023).

5. Data Analysis

Data analysis was conducted in stages using statistical software. First, prerequisite tests for analysis were performed, including a normality test (Kolmogorov–Smirnov) and a homogeneity of variance test (Levene’s test). Second, improvements in learning outcomes were analyzed using a paired-sample *t*-test to examine differences between the pretest and posttest scores within each group, as well as an independent-sample *t*-test to compare the two groups. In addition, the Normalized Gain (N-gain) score was calculated to measure the effectiveness of learning improvement. The N-Gain formula according to Hake (2002) is as follows:

$$N - Gain = \frac{\text{Score Posttest} - \text{score Pretest}}{\text{Score ideal} - \text{score pretest}}$$

Then, the N-Gain scores were interpreted according to the following categories:

Table 2. Normalized Gain Criteria

Nilai N-Gain	Kategori
$0,70 \leq g \leq 1,00$	High
$0,30 \leq g \leq 0,70$	Moderate
$0,00 < g < 0,30$	Low
$g = 0,00$	No Improvement
$-1,00 \leq g < 0,00$	A decrease occurred

The effect size of the model was calculated using Cohen’s *d* effect size, based on the formula proposed by Cohen (2013), as follows:

$$d = \frac{\overline{X}_1 - \overline{X}_2}{S_{gab}}$$

Where:

$\overline{X}_1$ = Mean of the experimental group

$\overline{X}_2$ = Mean of the control group

S_{gab} = Pooled standard deviation

Then, the *Cohen’s d effect size* values were interpreted based on the following criteria:

Table 4. Criteria for Cohen’s d Effect Size

Interval	Kategori
0,20	Small
0,50	Currently
0,80	Large
$\geq 1,20$	Very Large

3. RESULTS AND DISCUSSION

RESULTS

1. Description of Results

The descriptive results of the science literacy and HOTS learning practices are presented in Table 5 below.

Table 5. Descriptive Statistics of Science Literacy and HOTS

Variabel	Pretest Mean	Posttest Mean	N-Gain	Kategori
Literacy Science	55,80	83,40	0,63	High
HOTS	53,10	80,75	0,59	Currently

(Source: research findings, 2026)

Based on Table 5, the implementation of the Nanotechnology-Based Deep Learning-Oriented Hybrid PBL–STEAM Model resulted in a significant improvement in students' scientific literacy and Higher Order Thinking Skills (HOTS) after participating in learning using the Nanotechnology-Based Deep Learning-Oriented Hybrid PBL–STEAM Model. The average scientific literacy score increased from 55.80 in the pretest to 83.40 in the posttest, with an N-Gain value of 0.63, which falls into the high category. Meanwhile, students' HOTS increased from an average of 53.10 to 80.75, with an N-Gain value of 0.59, which falls within the moderate-to-high category.

These findings indicate that the implementation of a learning model integrating PBL, STEAM, and deep learning has a positive impact on improving students' scientific literacy and higher-order thinking skills in solid-state physics learning.

This improvement occurred because the learning model places students at the center of the learning process through the exploration of real-world problems based on nanotechnology in the context of solid-state physics concepts. The integration of the STEAM approach enables students to connect scientific concepts with technological and engineering applications, while the deep learning orientation promotes a deeper conceptual understanding. Previous research has shown that problem-based learning and STEAM integration can improve scientific literacy and students' critical thinking skills in the context of modern science education (Luh Putu Ritzki Wedanthi et al., 2024).

The increase in N-Gain of scientific literacy for each indicator is presented in Table 6 below:

Table 6. Distribution of N-Gain Improvement in Scientific Literacy by Indicator

Literacy Science Indicator	Mean Pretest	Mean Posttest	N-Gain	Catagory
Explaining scientific phenomena	56,20	84,10	0,64	High
Designing scientific investigations	54,80	82,70	0,61	High
Interpreting scientific data	56,40	83,40	0,62	High

(Source: research findings, 2026)

The data can be presented in the form of the following diagram:

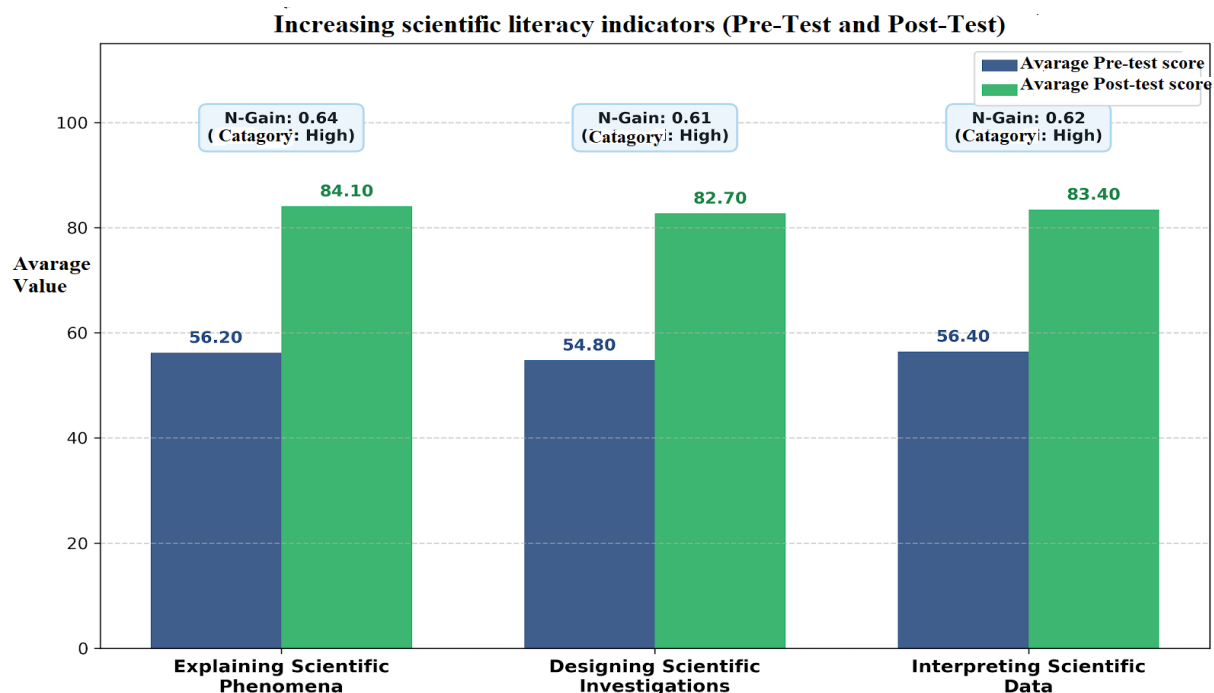


Figure 2. Distribution of N-Gain Improvement in Scientific Literacy by Indicator

Based on Table 6 and figure 2, all indicators showed improvement in the high category. The indicator *explaining scientific phenomena* showed an N-Gain value of 0.64, while the indicators *designing scientific investigations* and *interpreting scientific data* had N-Gain values of 0.61 and 0.62, respectively. These findings indicate that deep learning-oriented Hybrid PBL–STEAM-based instruction is effective in improving students' abilities to understand scientific concepts, analyze data, and design solutions based on physics concepts. This finding is consistent with previous studies showing that problem-based learning and interdisciplinary approaches can significantly improve students' scientific literacy (Li & Wu, 2025; Valeeva et al., 2023).

2. Analysis of Factors Influencing Scientific Literacy and HOTS

The results of the analysis of the factors influencing scientific literacy and Higher Order Thinking Skills (HOTS) using the *t-test* are presented in Table 7.

Table 7. Results of the Paired-Sample t-Test

Variable	t-value	Sig	Effect Size (Chone's d)	Interpretation
Science Literacy	8,21	0,000	1,50	Big
HOTS	7,64	0,000	1,39	Big

(Source: research findings, 2026)

Based on Table 7, the results of the analysis using a *paired-sample t-test* indicate a significant difference between the students' pretest and posttest scores. The significance values for scientific literacy and HOTS were both $p < 0.001$, indicating that the improvement in students' learning outcomes after participating in the learning process was statistically significant. Furthermore, the *effect size* analysis using Cohen's d yielded values of 1.50 for scientific literacy and 1.39 for HOTS, both of which fall into the large-effect category. This indicates that the implemented learning model had a very strong influence on improving students' scientific literacy and higher-order thinking skills. Thus, the implementation of the Nanotechnology-Based *Deep Learning*-Oriented Hybrid PBL–STEAM learning model not

only resulted in statistically significant differences but also produced a strong practical impact on improving students' scientific literacy and HOTS.

The large *effect size* values indicate that the learning approach employed was able to provide a more meaningful learning experience compared with conventional learning. The integration of *problem-based learning*, the STEAM approach, and *deep learning* orientation enabled students to become actively involved in scientific investigation and problem-solving processes related to nanotechnology phenomena in solid-state physics. This condition encouraged students to develop a deeper conceptual understanding while enhancing their critical and analytical thinking skills.

The effectiveness of this model was influenced by several key factors. First, the *problem-based learning approach* enabled students to develop analytical skills through solving authentic problems (Ampadu & Adjei-Boateng, 2018; Widiastuti et al., 2023). Second, the integration of STEAM encouraged interdisciplinary thinking, which strengthened students' conceptual understanding of science (Barkah et al., 2024; Herro & Quigley, 2016). Third, the *deep learning* orientation encouraged students not merely to memorize concepts but also to understand the relationships among concepts in depth. Recent studies have shown that learning approaches that promote active engagement and conceptual reflection can significantly improve scientific literacy in higher education (Qomah et al., 2025; Quigley & Herro, 2016).

1. Transformational Implications

Furthermore, students' responses to the learning model can be seen from the results of the analysis presented in Table 8 below:

Table 8. Students' Responses to the Learning Model

Aspek	Persentase (%)
More engaging learning	92
Understanding solid-state physics concepts becomes easier	88
Improving analytical skills	90
Connecting science with technology	94

(Source: research findings, 2026)

Data on student responses to the learning model can be presented in the form of the following diagram:

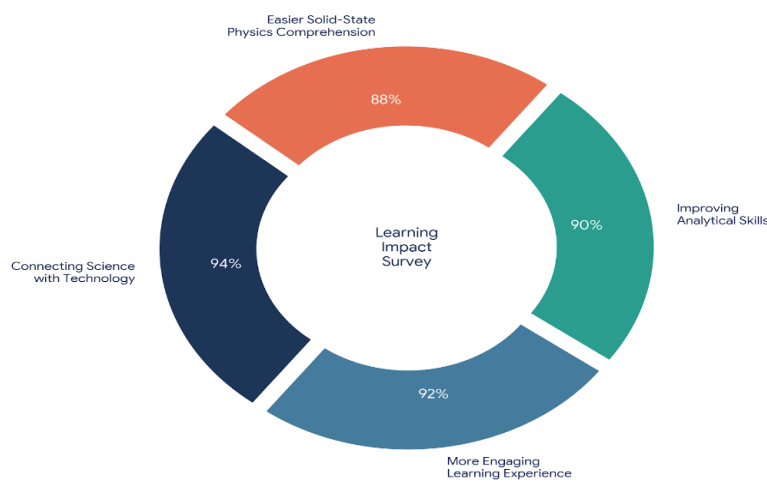


Figure 2. Students' responses to the learning model.

Based on Table 8 and figure 3, the questionnaire analysis showed that the majority of students responded positively to the implementation of the learning model. A total of 92% of students stated that the learning process became more engaging, while 90% of students felt that their analytical skills improved during the learning process. In addition, 94% of students stated that nanotechnology-based learning helped them understand the relationship between scientific concepts and technological applications. These findings confirm that integrating nanotechnology contexts into physics learning not only improves cognitive learning outcomes but also enhances students' motivation and engagement in the learning process.

The implications of these findings indicate that a learning approach combining PBL, STEAM, and *deep learning* can serve as an innovative strategy in higher science education. This model is not only relevant for improving students' scientific literacy but also supports the development of 21st-century skills, such as critical thinking, creativity, and complex problem-solving. The integration of nanotechnology as a learning context also provides a more authentic learning experience that is relevant to developments in modern science and technology (Davronova, 25M; OECD, 2023). Therefore, this model has the potential to be more broadly adapted within physics education curricula and other science disciplines.

DISCUSSION

Based on the research findings, the implementation of the Nanotechnology-Based Hybrid PBL–STEAM Model Oriented toward Deep Learning had a significant impact on improving students' scientific literacy and Higher Order Thinking Skills (HOTS) in the *Introduction to Solid State Physics* course. The learning outcome analysis indicated that students who participated in this instructional model demonstrated greater improvements in conceptual understanding, analytical ability, and problem-solving skills compared to those who experienced conventional instruction. This finding suggests that the integration of Problem-Based Learning (PBL), the STEAM approach, and a deep learning orientation can create a more constructive and reflective learning environment. These findings also reinforce the argument that problem-based and interdisciplinary learning are essential strategies for enhancing students' scientific literacy in modern science education (OECD, 2023; Ramadhan et al., 2026).

Within the social and cultural context of higher education in Indonesia, improving scientific literacy has become a strategic issue due to the existing gap between students' conceptual competencies and the demands of rapidly advancing global science and technology. Reports from the *Programme for International Student Assessment (PISA)* indicate that scientific literacy levels in many developing countries remain at a moderate to low level, highlighting the need for pedagogical innovations that promote more meaningful and contextualized learning experiences (OECD, 2023). In this regard, the integration of nanotechnology into physics instruction provides a strong connection between scientific concepts and contemporary technological developments. The use of advanced technological contexts in science learning has been shown to increase students' learning motivation and strengthen their conceptual understanding, as they are able to recognize the direct relationship between theoretical knowledge and its real-world applications (Andriyani, 2024). Therefore, the instructional model developed in this study serves not only as a pedagogical strategy but also as an effort to bridge the gap between science education in higher education and the advancement of global technology.

Theoretically, the findings of this study can be explained from a constructivist perspective, which emphasizes that knowledge is actively constructed through meaningful learning experiences. The *problem-based learning* approach provides students with opportunities to develop conceptual understanding through the exploration of real-world problems. Thus, the learning process focuses not only on knowledge transfer but also on

independent knowledge construction (Anisa Aprina et al., 2024). Furthermore, the integration of the STEAM approach enables students to connect physics concepts with other disciplines, such as technology and engineering, thereby fostering a more holistic conceptual understanding. This approach is consistent with *deep learning pedagogy*, which emphasizes the importance of learning that promotes critical reflection, knowledge integration, and the ability to transfer concepts to new contexts (Mukhoyaroh et al., 2025). Therefore, the improvement in scientific literacy and HOTS identified in this study can be understood as the result of an interaction among problem-based learning, interdisciplinary integration, and deep learning processes.

One important insight gained from this study is that pedagogical innovation in science education does not depend solely on instructional methods but also on the scientific context used in the learning process. In this study, the use of nanotechnology as a contextual framework provided students with opportunities to explore solid-state physics concepts through phenomena relevant to modern technological developments. This finding indicates that integrating cutting-edge scientific content with innovative learning strategies can significantly improve the quality of learning. This finding is consistent with the studies by Nabila et al. (2025) and Sakti et al. (2021), which emphasize that technology-contextualized science learning can enhance scientific literacy because students are engaged in more authentic scientific investigation processes. Thus, learning approaches that integrate cutting-edge technological contexts have considerable potential to improve the quality of science education in higher education.

Compared with previous studies, the findings of this study reinforce the evidence that problem-based learning approaches and the integration of STEM or STEAM have positive effects on the development of scientific literacy and higher-order thinking skills. Pranata et al. (2023) demonstrated that the integration of STEM into science learning can improve students' problem-solving abilities and conceptual understanding. Another study by Hidayat et al. (2024) also showed that an integrated STEM approach can enhance knowledge transfer abilities in science learning. However, most previous studies have examined PBL, STEM, or deep learning approaches separately. This study offers a novel contribution by integrating these three approaches into a single nanotechnology-based learning model. Therefore, this study extends the literature on science education innovation by demonstrating that the integration of multiple pedagogical approaches can produce more significant impacts on the development of students' scientific competencies.

Based on the findings of this study, several important implications can be identified for the development of science education in higher education. First, physics curricula should integrate problem-based and interdisciplinary learning approaches to enhance students' scientific literacy. Second, the use of cutting-edge technological contexts, such as nanotechnology, can increase the relevance of learning to developments in modern science and technology. Third, lecturers need to develop learning strategies that promote *deep learning* through scientific investigation activities, reflective discussions, and research-based projects. In addition, future studies are recommended to examine the effectiveness of this learning model in various other science courses and to employ more sophisticated analytical methods, such as *structural equation modeling* (SEM), to comprehensively examine the relationships among learning variables. The implementation of these recommendations is expected to support the development of science education that is more innovative and relevant to the needs of the 21st century.

4. CONCLUSION

This study aimed to analyze the effectiveness of the Nanotechnology-Based Deep Learning-Oriented Hybrid PBL–STEAM Model in improving students' scientific literacy and Higher Order Thinking Skills (HOTS) in the Introduction to Solid State Physics course. The

results showed that the implementation of this learning model significantly improved students' scientific literacy and higher-order thinking skills compared with conventional learning approaches. The integration of problem-based learning, the interdisciplinary STEAM approach, and deep learning orientation enabled students to develop a deeper conceptual understanding through scientific investigation, exploration of authentic problems, and active engagement in learning activities. Thus, this study contributes scientifically to the development of an innovative learning model capable of integrating modern pedagogical approaches with cutting-edge technological contexts, such as nanotechnology, in physics education.

From a theoretical perspective, this study enriches the literature on science learning innovation by integrating three major pedagogical approaches—problem-based learning, STEAM education, and deep learning pedagogy—into a single learning framework based on the context of nanotechnology. This integration provides a new perspective for understanding how interdisciplinary learning approaches can simultaneously enhance scientific literacy and higher-order thinking skills. In addition, this study offers a methodological reflection on the importance of using a quasi-experimental research design combined with inferential statistical analysis to evaluate the effectiveness of learning models more objectively. This methodological approach enables researchers to obtain a more comprehensive understanding of the relationship between innovative learning strategies and the improvement of students' scientific competencies in the context of higher education.

Practically, the findings of this study have important implications for curriculum development and learning practices in higher physics education. The implementation of a PBL–STEAM-based learning model oriented toward deep learning can serve as an effective strategy for improving students' scientific literacy while developing the higher-order thinking skills required to address the challenges of the 21st century. Furthermore, the use of nanotechnology contexts in physics learning can enhance the relevance of learning materials to developments in modern science and technology. For future research, it is recommended that this learning model be tested in various other science disciplines and involve more complex analytical methods, such as Structural Equation Modeling (SEM) or mixed-method research, to gain a deeper understanding of the pedagogical mechanisms influencing the development of students' scientific literacy and HOTS. Future studies could also explore the integration of digital technology and project-based learning to further strengthen the effectiveness of innovative learning models in science education.

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