JPF | Volume 13 | Number 3 | 2025 | 416 - 428

p - ISSN: 2302-8939
e - ISSN: 2527-4015

Jurnal Pendidikan Fisika

https://journal.unismuh.ac.id/index.php/jpf

DOI: 10.26618/ttrea958

Effectiveness of Integrating Deep Learning into Problem-Based Learning with PhET Simulations to Enhance Students' Problem-Solving Skills

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Received: May 26, 2025; Accepted: August 15, 2025; Published: September 13, 2025

Abstract – *Problem-solving skills are widely recognized as essential competencies in physics education and central to preparing students for the demands of twenty-first-century learning. However, students often struggle to connect abstract physics concepts with real-world applications when learning is dominated by conventional approaches that emphasize rote memorization rather than critical engagement. To address this gap, this study investigated the effectiveness of integrating a deep learning approach into the Problem-Based Learning (PBL) model supported by PhET interactive simulations in enhancing students' problem-solving skills. The research employed a pre-experimental one-group pretest–posttest design involving 15 eleventh-grade students at SMA Sultan Agung 1 Semarang. Students completed validated problem-solving assessments covering five dimensions: reading, comprehension, transformation, process skills, and encoding. The results revealed a significant increase in mean scores from 57 on the pretest to 81 on the posttest, representing an improvement of 24 points (42.1%) and yielding a normalized gain (N-Gain) of 0.63, categorized as moderate. Dimension-level analysis showed consistent improvement across all aspects, with the largest gains observed in transformation and encoding, highlighting enhanced higher-order thinking, reflective reasoning, and metacognitive awareness. The novelty of this research lies in combining deep learning strategies, PBL, and PhET simulations in a unified instructional framework, which has rarely been explored in physics education. The findings demonstrate that this integrated approach not only strengthens students' ability to analyze and solve problems but also fosters meaningful conceptual understanding by linking theory with observable phenomena. This study contributes to the field of physics education by providing empirical evidence and a practical model that aligns with constructivist principles, offering guidance for teachers and researchers in developing innovative instructional designs to comprehensively improve problem-solving skills.*

Keywords: *deep learning approach; PhET simulations; physics education; problem-based learning; problem-solving skills*

I. INTRODUCTION

Problem-solving skills are widely recognized as central competencies in twenty-first-century education and are particularly crucial in science subjects such as physics. Developing these skills is not only about arriving at correct answers but also about cultivating the ability to analyze problems critically, construct logical reasoning, and apply scientific principles to real-world contexts (Hidaayatullaah et al., 2020; Ulya, 2016). As physics concepts are often abstract and mathematically demanding, students frequently struggle to connect theory with observable phenomena when learning relies on conventional approaches. Recent studies have underscored the importance of educational models that emphasize inquiry, reflection, and higher-order thinking as essential elements in fostering problem-solving abilities (Mashami et al., 2023; Gao et al., 2024). Within this context, the integration of innovative learning approaches supported by interactive media has been highlighted as an effective pathway to enhance student learning outcomes in science education (Sondole et al., 2023).

In response to these challenges, Problem-Based Learning (PBL) has emerged as a widely researched and effective pedagogical strategy for supporting the development of problem-solving skills. PBL promotes student-centered learning by engaging learners in the process of identifying, analyzing, and solving authentic problems, thereby motivating them to think independently and collaboratively (Saputra, 2021). Empirical evidence suggests that PBL enhances students' motivation, critical thinking, and conceptual understanding across diverse science topics (Gulo, 2022; Mayasari et al., 2022). At the same time, the deep learning approach, understood in the context of education rather than artificial intelligence, provides a complementary framework by encouraging meaningful and integrative understanding of concepts rather than surface-level memorization (Entwistle, 2023). Deep learning emphasizes active engagement, reflection, and the ability to connect prior knowledge with new information, all of which are necessary for strengthening higher-order cognitive processes. The convergence of these two approaches, PBL and deep learning offers the potential to transform physics education by creating a learning environment where problem solving is not only practiced but also deeply internalized.

Despite the documented benefits of both PBL and deep learning approaches, several persistent challenges remain. Many students continue to struggle with bridging the gap between abstract theory and real-world application because traditional learning environments often prioritize rote memorization over critical engagement (Djonomiarjo, 2020; Mashami et al., 2023). This misalignment limits students' capacity to develop robust problem-solving strategies, leaving them underprepared for the complexities of twenty-first-century scientific inquiry. Moreover, conventional classroom practices frequently lack interactive components that allow learners to visualize, manipulate, and test scientific principles dynamically. Without such opportunities, students may achieve partial or fragmented understanding that does not translate into effective problem-solving competence. Therefore, an urgent need exists to design instructional models that integrate student-centered approaches with interactive technologies to more effectively cultivate deep and sustainable learning in physics education (Estrada-Molina et al., 2024; Suglo, 2024).

Several studies have reported promising outcomes from the application of deep learning strategies and interactive media in science education. For instance, Huang and Annamalai (2024) found that deep learning could be significantly enhanced through blended learning designs based on Small Private Online Courses (SPOCs) within a community of inquiry framework, which integrates cognitive, social, and teaching presence. Estrada-Molina et al. (2024), in a systematic review, concluded that the application of deep learning in open learning environments consistently improves student engagement and conceptual understanding. Suglo (2024) further demonstrated that deep learning-based activities in mathematics classes positively influence academic achievement, underscoring the potential of such approaches across different domains. At the same time, Çalışkan and Altun (2025) highlighted that classroom engagement and cognitive flexibility contribute directly to creative problem-solving, while Zerdali and Eğmir (2025) emphasized the role of metacognitive awareness in developing reflective problem-solving strategies. Collectively, these studies affirm the importance of embedding deep learning principles in instructional models that seek to cultivate higher-order thinking and problem-solving abilities.

In parallel, the role of interactive media in facilitating conceptual understanding and problem-solving cannot be overlooked. PhET simulations, developed by the University of Colorado, have been widely adopted as effective tools for visualizing and exploring scientific phenomena (Haryadi & Pujiastuti, 2020; Inayah & Masruroh, 2021). These simulations allow students to manipulate variables, test predictions, and observe dynamic relationships, thereby supporting both inquiry-based learning and reflective reasoning. Empirical research has shown that the integration of PhET into science instruction enhances student engagement, conceptual understanding, and critical thinking skills (Mashami et al., 2023; Saudelli et al., 2021). When combined with PBL, PhET simulations provide a rich learning environment in which abstract concepts can be contextualized, explored, and tested, leading to deeper cognitive engagement and more meaningful problem-solving experiences (Pranata, 2024; Saenboonsong & Poonsawad, 2024). Despite these promising developments, however, relatively few studies have examined the combined application of PBL, deep learning, and PhET simulations in a unified framework for physics education. Existing works often address these components in isolation, leaving a gap in understanding how their integration can comprehensively strengthen both conceptual mastery and problem-solving competence.

This gap highlights the need for empirical studies that explore the effectiveness of integrating deep learning principles into PBL models supported by interactive simulations such as PhET. While previous studies have validated the benefits of each component individually—PBL for fostering inquiry and collaboration (Saputra, 2021; Gulo, 2022), deep learning for promoting reflective and meaningful understanding (Entwistle, 2023), and PhET for enhancing visualization and scientific reasoning (Inayah & Masruroh, 2021; Mashami et al., 2023)—the combined impact of these strategies remains underexplored in the context of physics education. This study seeks to address that gap by investigating how the integration of these three elements can collectively foster problem-solving skills, support higher-order thinking, and align learning practices with the principles of constructivist education (Zerdali & Eğmir, 2025; Estrada-Molina et al., 2024).

Therefore, the purpose of this research is to analyze the effectiveness of integrating the deep learning approach into the PBL model supported by PhET simulations in enhancing students' problem-solving skills in physics. The novelty of this study lies in its unified framework, which combines three approaches that have rarely been studied together in empirical research. By situating deep learning within PBL and augmenting it with interactive PhET simulations, this study contributes new insights into how physics instruction can be designed to simultaneously cultivate conceptual mastery, reflective reasoning, and practical problem-solving competence. In doing so, it offers both theoretical contributions to the development of innovative instructional models and practical implications for educators seeking to strengthen problem-solving skills in secondary school physics education.

II. METHODS

This study employed a quantitative approach with a pre-experimental design of the one-group pretest–posttest type. Such a design involves the selection of a single group of participants who undergo treatment, with learning outcomes measured before and after the intervention without a comparison group. The one-group pretest–posttest model has been widely utilized in educational research to evaluate the effectiveness of innovative instructional interventions, particularly when experimental control is limited by contextual constraints (Muhajir et al., 2015). Its strength lies in capturing the immediate effect of a treatment on the same cohort, thereby allowing researchers to determine relative gains in performance within a short-term framework. In this study, the objective was to examine how integrating a deep learning approach into the PBL model, supported by PhET interactive simulations, can improve students' problem-solving skills in physics.

The participants consisted of 15 students from Class XI.1 at SMA Sultan Agung 1 Semarang, selected purposively based on specific criteria. The students chosen had no prior experience with the PBL model integrated with deep learning strategies and PhET media, ensuring that the treatment represented a novel instructional experience. Purposive sampling is considered appropriate in small-scale educational research where the aim is to select participants who can provide rich and relevant data (Lopez-Jimenez et al., 2021). By focusing on a homogenous group, this study minimized variability in prior exposure and enhanced the internal validity of the findings.

The primary instrument employed was a problem-solving ability test consisting of two essay questions designed to assess students' capacity to engage in systematic scientific reasoning. These questions were validated through expert review, involving three physics education specialists who examined content validity, linguistic clarity, and alignment with the measured aspects of problem solving. Expert validation is a critical step in instrument development to ensure construct relevance and fairness in measurement. Feedback from validators was incorporated to refine the test prior to administration. The test measured five specific aspects of problem solving: reading, comprehension, transformation, process skills, and encoding.

The research procedure began with the administration of a pretest to establish students' baseline abilities. Students were then given 40 minutes of instruction using the PBL model integrated with deep learning strategies. At each stage of the PBL process, elements of deep learning were embedded to encourage students to reflect, connect new information with prior knowledge, and elaborate their understanding. For example, students first observed phenomena through PhET simulations, then reflected on observed patterns and formulated hypotheses. They were encouraged to explore alternative explanations by linking multiple physics concepts and elaborated their findings through group discussions and solution presentations. This sequence reflects the emphasis of deep learning on interconnection, reflection, and critical analysis (Entwistle, 2023).

The integration of PhET simulations was a central feature of the intervention. As interactive exploration tools, PhET simulations allowed students to manipulate variables such as temperature, velocity, or pressure to visualize relationships, test predictions, and verify solutions. This interactive element supports inquiry and reflective reasoning by making abstract concepts observable and manipulable (Inayah & Masruroh, 2021). During simulation use, the teacher facilitated learning by posing guiding questions that directed students toward deeper reasoning, thereby reinforcing the principles of constructivist pedagogy. Prior research indicates that technology-enhanced environments such as PhET foster critical thinking and metacognitive skills, which are essential for problem solving (Mashami et al., 2023).

After the instructional phase, students completed a posttest consisting of the same problem-solving tasks as in the pretest. This repetition allowed direct comparison of performance before and after the intervention, providing an objective measure of learning gains. The problem-solving test required students to demonstrate both procedural and conceptual mastery. Specifically, each item was scored across five analytic categories: identifying known information, articulating the question to be answered, determining the relevant equations or principles, outlining steps of solution, and drawing accurate conclusions. Each category was awarded a maximum of ten points if complete, five points if partially correct, and zero if omitted. This analytic scoring system ensured that the evaluation captured not only final answers but also the underlying reasoning process, consistent with the view that problem solving in physics involves systematic engagement with concepts and procedures (Lopez-Jimenez et al., 2021).

For data analysis, the pretest and posttest scores were processed using the normalized gain (N-Gain) index to measure the proportional improvement relative to the maximum possible gain. The N-Gain is widely employed in physics education research as it provides an equitable assessment of instructional impact by considering differences in baseline scores (Hake, 1999; Mashami et al., 2023). Gains were categorized into three levels: high ($g \geq 0.7$), moderate ($0.3 \leq g < 0.7$), and low ($g < 0.3$), as shown in Table 1. In addition to descriptive statistics such as mean scores, the N-Gain values provided insight into the extent to which students' problem-solving abilities improved through the integration of deep learning into PBL with PhET simulations.

Table 1. Category of N-gain score

No	Gain score	Criteria
1	$g \geq 0.7$	High
2	$0.3 \geq g > 0.7$	Moderate
3	$g < 0.3$	Low

III. RESULTS AND DISCUSSION

The results of the pretest and posttest assessments of students' problem-solving skills are presented in Figure 1. The mean pretest score was 57, while the mean posttest score increased to 81, representing a 24-point improvement. This gain corresponds to a relative increase of approximately 42.1%, indicating substantial progress in students' performance following the implementation of the PBL model integrated with deep learning strategies and PhET interactive simulations. The N-Gain analysis yielded a value of 0.63, which falls within the moderate improvement category. This suggests that, although students' problem-solving abilities significantly improved, further enhancement remains possible.

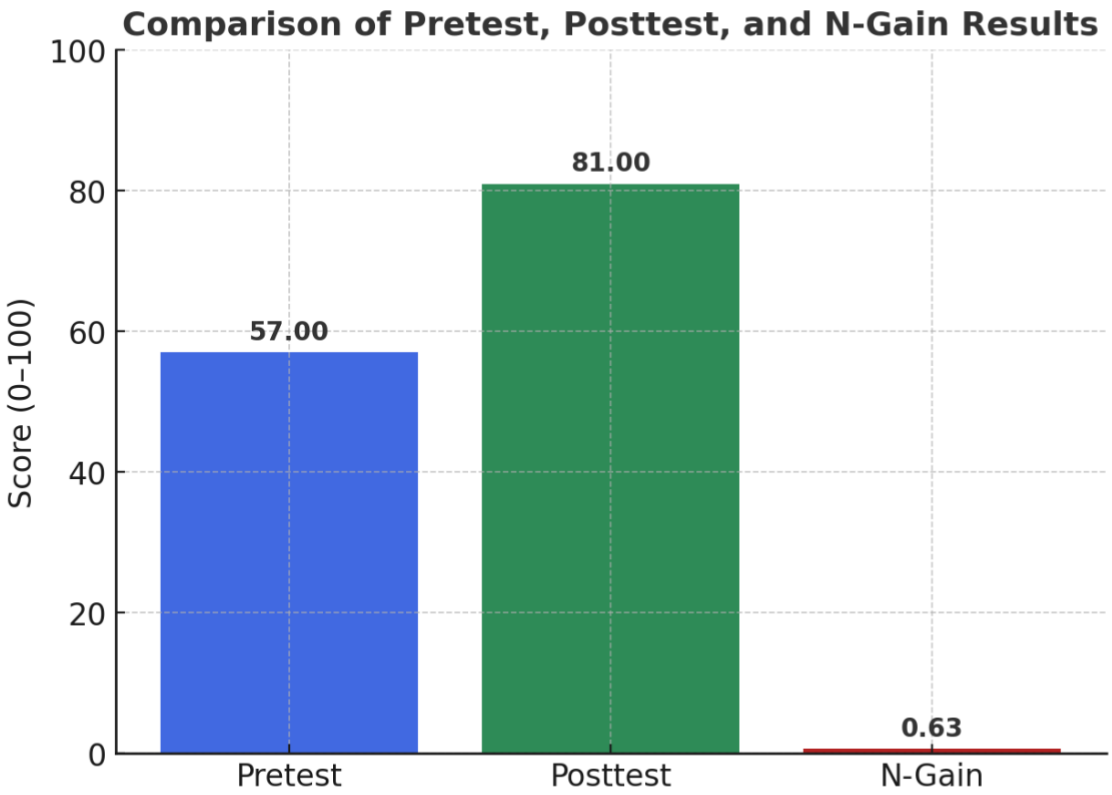

Figure 1. Pretest and posttest results of problem-solving ability

The scoring rubric employed for both tests was designed to capture not only the accuracy of final answers but also the systematic reasoning process. Students were required to demonstrate their ability across five dimensions: identifying known information, articulating the problem to be solved, determining relevant equations or principles, outlining procedural steps, and drawing appropriate conclusions. Each dimension was scored analytically, ensuring a comprehensive evaluation of problem-solving competence. During the pretest, most students were able to provide basic information and recall equations but frequently struggled to formulate coherent solution strategies or arrive at accurate conclusions. In contrast, the posttest responses revealed greater depth of reasoning, clearer articulation of procedural steps, and more accurate conclusions, reflecting the impact of the instructional intervention.

Figure 2 illustrates the average scores across the five problem-solving dimensions. Improvements were evident in all categories. Reading skills increased from approximately 80 to nearly 100, comprehension improved from 75 to about 95, and transformation rose from 70 to over 90. Similarly, process skills advanced from 75 to 95, while the most pronounced growth occurred in encoding, which improved from around 78 to nearly 98. These results indicate that the intervention was particularly effective in strengthening students' abilities to transform problems into accurate representations and to encode their solutions through reflective and evaluative reasoning (Alniak-Daye & Ogan-Bekiroglu, 2025). Collectively, the findings suggest that the combined application of deep learning, PBL, and PhET simulations effectively enhanced both lower-order and higher-order aspects of problem-solving skills.

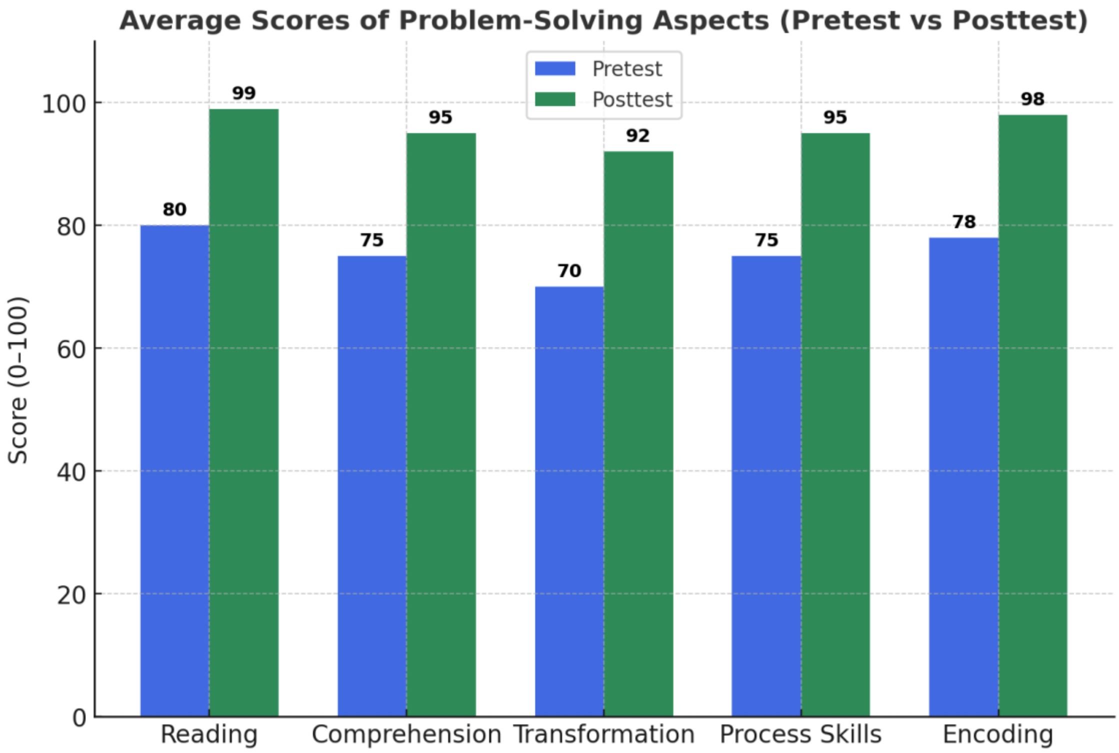

Figure 2. Average scores for the five aspects of problem-solving

The findings of this study demonstrate that the integration of deep learning strategies into a PBL framework supported by PhET simulations significantly enhances students' problem-solving abilities across multiple dimensions. The observed improvement in the posttest mean score, as well as the N-Gain of 0.63, indicates that students not only improved their ability to solve problems correctly but also developed more structured reasoning and reflective evaluation skills. These results align with earlier reports that PBL can foster student-centered inquiry, collaboration, and critical thinking by situating learning within authentic contexts (Saputra, 2021; Gulo, 2022). Furthermore, the embedding of deep learning elements into PBL strengthened conceptual understanding and reflective engagement, which are crucial in cultivating higher-order cognitive skills in science education (Entwistle, 2023; Gao et al., 2024).

The dimension-specific analysis offers deeper insight into how these instructional strategies shaped student learning. For instance, the substantial gain in the transformation dimension, where scores increased from 70 to 92, indicates that students became more adept at translating verbal or conceptual problems into visual and mathematical representations. This echoes the findings of Pranata (2024) and Saenboonsong and Poonsawad (2024), who observed that interactive media such as PhET simulations and gamified learning environments can enhance learners' representational and creative problem-solving skills. Likewise, the dramatic improvement in the encoding dimension—from 78 to 98—underscores the importance of reflective reasoning and metacognitive awareness in consolidating problem-solving competence. This resonates with the work of Çalışkan and Altun (2025) and Zerdali and Eğmir (2025), who emphasized the direct role of cognitive flexibility and reflective thinking in fostering students' ability to validate and generalize solutions.

Equally noteworthy are the consistent gains in reading and comprehension, which increased to nearly 100 and 95, respectively. These improvements suggest that embedding deep learning principles into PBL encouraged students to engage more thoroughly with the problem context, linking prior knowledge to new information through active reflection. Similar outcomes have been documented in research on inquiry-based and metacognition-focused instructional designs, which highlight the role of deep learning in enhancing students' initial engagement with scientific problems and their subsequent capacity for conceptual understanding (Dulger & Ogan-Bekiroglu, 2024; Estrada-Molina et al., 2024; Nugroho, 2020; Suglo, 2024). Taken together, these findings reaffirm that the combined framework of PBL, deep learning, and PhET simulations provides a robust pathway for developing both procedural and conceptual aspects of problem solving (Friantini & Winata, 2019; Nugroho, 2020; Özpınar & Arslan, 2023).

From a theoretical perspective, this study strengthens the constructivist view of learning, which posits that knowledge is constructed through active engagement, reflection, and interaction with meaningful contexts (Saudelli et al., 2021). The improvements observed across all five problem-solving dimensions confirm that learning environments that integrate student-centered strategies with interactive technologies can effectively bridge the gap between abstract physics concepts and real-world application. Such findings are consistent with prior evidence that the use of PhET simulations improves scientific reasoning and problem-solving by enabling students to visualize and manipulate variables in dynamic systems (Alniak-Daye & Ogan-Bekiroglu, 2025; Haryadi & Pujiastuti, 2020; Inayah & Masruroh, 2021; Mashami et al., 2023). When paired with the structured inquiry of PBL, these simulations appear to provide fertile ground for higher-order reasoning, reflective evaluation, and collaborative problem solving (Budiarti, 2021).

Practically, the results of this study provide educators with empirical support for adopting integrated instructional models that combine pedagogical strategies and technological tools to foster deeper learning outcomes. The framework applied here demonstrates that improvements are not confined to surface-level skills but extend to reflective and metacognitive domains, which are essential for long-term knowledge retention and transfer (Renninger et al., 2025). Nevertheless, the moderate classification of the N-Gain indicates that while the approach is effective, it may be further optimized by extending the duration of instruction, incorporating more diverse problem scenarios, or combining with blended learning strategies shown to enhance deep learning in other contexts (Herayanti et al., 2020; Huang & Annamalai, 2024; Pimdee et al., 2024).

IV. CONCLUSION AND SUGGESTION

This study provides empirical evidence that integrating a deep learning approach into a PBL model supported by PhET simulations meaningfully improves students' problem-solving performance. Across a cohort of eleventh-grade students, the mean score increased from 57 (pretest) to 81 (posttest), an absolute gain of 24 points (42% relative increase), with a normalized gain of 0.63 indicating moderate effectiveness. Dimension-level results corroborate the aggregate gains: all five assessed aspects (reading, comprehension, transformation, process skills, and encoding) improved, with the largest advances observed in transformation and encoding—signals of strengthened higher-order reasoning and reflective evaluation. Collectively, the results show that the combined PBL, deep learning, and PhET framework enhances both procedural fluency and conceptual understanding in physics problem solving.

The study is limited by its pre-experimental one-group design, small sample size, and short instructional duration, which constrain causal inference and generalizability. Future research should employ comparative or randomized designs with larger, more diverse samples, extend the intervention over multiple units or semesters, and examine retention and transfer across topics and contexts. It will also be valuable to contrast this integrated approach with alternative technology-enhanced pedagogies and blended formats to identify boundary conditions and cost-effectiveness. Even with these limitations, this work contributes to physics education by offering a coherent, classroom-ready model that operationalizes constructivist principles—linking inquiry, deep cognitive engagement, and interactive simulations—while providing quantitative evidence of multi-aspect improvements in students' problem-solving competence.

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