JPF | Volume 13 | Number 2 | 2025 | 119 - 132

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

Jurnal Pendidikan Fisika

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

DOI: 10.26618/jpf.v13i2.17432

The Effectiveness of a Renewable Energy E-Worksheet in STEM-Project-Based Learning to Improve Students' Critical Thinking and Collaboration Skills

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Received: January 03, 2025; Accepted: March 21, 2025; Published: April 26, 2025

Abstract – *The integration of 21st-century competencies, particularly critical thinking and collaboration, has become essential in physics education. However, the abstract concept of renewable energy poses learning challenges for high school students, despite its fundamental importance in physics education and relevance to sustainability. This study investigates the effectiveness of a STEM-project-based electronic worksheet (e-worksheet) designed to enhance students' critical thinking and collaboration abilities. A quasi-experimental design with a randomized cluster sampling technique was used, involving 50 Grade X students from SMA Negeri 1 Subang. The experimental group received instruction through a renewable energy e-worksheet aligned with STEM and Project-Based Learning (PjBL) models, while the control group experienced conventional teaching. Data were collected through pre-and post-tests and questionnaires and analyzed using N-Gain and Cohen's d-effect size. The results show high N-Gain scores in the experimental group for critical thinking (0.72) and collaboration skills (0.75), in contrast to moderate scores in the control group. This suggests a significant learning gain attributable to the integrated e-worksheet. The study's novelty lies in the integration of a renewable energy project, digital interactivity via Liveworksheets, and structured STEM-PjBL syntax, providing a holistic, engaging learning experience. The research concludes that STEM-PjBL e-worksheets are effective in promoting 21st-century competencies and can address instructional gaps in current physics education. This approach contributes to developing sustainable thinking and teamwork abilities, preparing students for future interdisciplinary challenges in science and technology.*

Keywords: *collaboration skills; critical thinking skills; physics e-worksheet; renewable energy; STEM-PjBL*

I. INTRODUCTION

In the 21st century, every aspect of human life must keep pace with the rapid development of technology and science. As science and technology evolve at an accelerated rate, education plays a pivotal role in helping individuals adapt to global developments and competition (Yusuf & Widyaningsih, 2019). Education aims to foster the development of skills that equip students to navigate and respond effectively to the challenges and changes of the modern world (Asrizal et al., 2022). Success in education is largely determined by the ability of educators to effectively integrate both theoretical knowledge and practical skills (Sulaeman et al., 2022; Martínez-Borreguero et al., 2022). These abilities enable teachers to design lessons that are not only engaging and easy to understand but also encourage active participation from students (Büyükdede & Tanel, 2019). Such success is possible when teachers fulfill their roles well, fostering student involvement in the learning process.

The learning models designed today are expected to promote the development of essential 21st-century skills, known as the 4C skills: critical thinking, creativity, collaboration, and communication. In Indonesia, these skills are explicitly integrated into the project-oriented Merdeka Belajar curriculum, which aims to strengthen the *Pancasila* student profile. This curriculum is developed around specific themes determined by the government (Kemendikbud, 2021). The *Merdeka Belajar* curriculum promotes STEM (Science, Technology, Engineering, and Mathematics) skills in an integrated and comprehensive manner, encouraging students to engage with real-world issues and solve complex problems through cross-disciplinary learning (Kemendikbud, 2021). By implementing this curriculum, both educators and students can better understand scientific concepts, fostering development and improving learning outcomes.

One educational approach that fits well within the *Merdeka Belajar* framework is project-based learning (PjBL), which has proven effective in enhancing 21st-century skills (Suherman et al., 2020). PjBL allows students to engage with complex problems that require critical thinking to solve, encouraging them to conduct research and analyze the problems in order to devise solutions (Putri et al., 2021). Despite its effectiveness, the use of PjBL within the *Merdeka Belajar* curriculum is not yet widespread, with many teachers still relying on traditional teaching methods (Purwaningsih et al., 2020). In a PjBL setting, students create tangible artifacts at the end of their learning journey, allowing teachers to monitor their progress and activities during the lessons (Alemneh & Gebrie, 2024). Implementing this model has been shown to significantly improve students' abilities, including their learning outcomes and 4C skills (Guo et al., 2020). Research by Putri et al. (2021) supports this, showing that students taught using PjBL developed better critical thinking skills than those taught using traditional methods, with an N-Gain of 75.40%, which indicates a high level of improvement. In addition, using the STEM approach has been shown to improve both academic and practical outcomes for students (Yik et al., 2022; Fitriani & Festiyed, 2023). A combination of STEM and PjBL has been proven to boost problem-solving abilities (Butai et al., 2021), enhance higher-order thinking skills, and reduce students' misconceptions (Martawijaya et al., 2023). This combined approach is considered highly effective, if it is supported by appropriate teaching materials, such as student worksheets.

One innovation in teaching materials that can help maximize the use of technology in education is the electronic student worksheet or e-worksheet. Despite their potential, e-worksheets remain underutilized in classroom settings (Sarah & Rani, 2020). E-worksheets help overcome time and space limitations (Wahyuni et al., 2021) and serve as interactive tools that ease the teaching process, allowing students to engage in the learning process in a more enjoyable and less monotonous manner. Furthermore, well-designed worksheets can be aligned with the character values students are expected to develop (Sarah & Rani, 2020). By involving students in sustainable projects and environmental activities in a fun context, these worksheets help foster greater engagement (Amalya et al., 2021). The specific focus of this research is on the development of STEM-based e-worksheets that integrate the PjBL model.

Critical thinking is one of the most essential 21st-century skills for students. It is a core goal of the *Kurikulum Merdeka* movement, aligning with the characteristics outlined in the Pancasila student profile (Amalya et al., 2021). Developing critical thinking prepares students to analyze and solve problems across various disciplines (Alemneh & Gebrie, 2024), supporting intellectual self-actualization (Putri et al., 2021), and equipping them with the skills needed to thrive in the 21st century (Asrizal et al., 2022). The objective of critical thinking is to make informed decisions based on careful consideration of available evidence and logical reasoning (Martawijaya et al., 2023). However, students' critical thinking skills in Indonesia are still relatively underdeveloped, and often categorized as low (Pradana et al., 2020). Interviews with physics teachers at SMA Negeri 1 Subang reveal that only a small number of students actively participate by asking questions, while the majority remain passive during lessons. Many students are not accustomed to engaging with Higher-Order Thinking Skills (HOTS) questions and often fail to fully engage with them. Thus, it is crucial to continuously integrate the development of critical thinking into the learning process.

Collaboration skills are just as vital as critical thinking for students, particularly when solving complex problems in science and technology. Collaborative learning enables students to work together in groups, sharing knowledge and experiences to complete physics projects, such as designing a waterwheel or conducting experiments. This teamwork not only strengthens their understanding of physics concepts but also enhances their ability to collaborate effectively (Santoso et al., 2021). Collaboration is essential for students to work productively in teams, completing tasks efficiently and solving problems more effectively (Safarini, 2019). Additionally, students must develop the ability to show tolerance (Kuo et al., 2019), responsibility (Conde et al., 2019), respect (Nurtanto et al., 2020), and wisdom when facing complex problems (Santoso et al., 2021). Hence, it is necessary to develop appropriate teaching materials and employ suitable learning models that support the improvement of collaboration skills.

Physics education is particularly relevant to the development of 21st-century skills. Physics explains natural phenomena and the processes that govern them (Khoiri et al., 2023), and understanding its concepts is a key determinant of student success (Mundilarto & Ismoyo, 2017). Nevertheless, many students find physics to be a challenging subject (Yuliati et al., 2018). One of the reasons for this difficulty is that students perceive physics as requiring knowledge of other disciplines, such as mathematics and complex concepts (Aprillia et al., 2021). Renewable energy, in particular, is considered a difficult subject (Febriansari et al., 2022) yet students need to understand, it as it relates to global, regional, and political issues, as well as everyday life (Aprillia et al., 2021). Mastery of renewable energy is also a crucial step toward achieving energy security in the future (Wulanndari & Admoko, 2023). Efforts to enhance students' understanding of renewable energy can be made by linking theoretical concepts to real-world phenomena (Asrizal et al., 2024), a practice well-suited to PjBL that offers meaningful learning experiences.

Based on these considerations, the researcher aims to develop teaching materials in the form of STEM-based electronic worksheets integrated with the PjBL model. These materials are designed to help students improve their critical thinking and collaboration skills, specifically in the context of renewable energy education. This research focuses on the topic of renewable energy for Class X Phase E at SMA Negeri 1 Subang during the 2024/2025 academic year. By integrating PjBL with Liveworksheets technology, this study seeks to contribute to the development of student's critical thinking and collaboration skills while addressing the challenges of 21st-century education, which increasingly demands the integration of technology and innovative approaches to teaching and learning.

II. METHODS

This research adopts a quasi-experimental design with non-equivalent control group design, conducted from October to November 2024 in Subang. The study involved a total sample of 50 students from Class X Phase E. The sample was divided into experimental and control groups to evaluate the effectiveness of the renewable energy e-worksheet in STEM-PjBL. The sampling technique used was randomized cluster sampling, ensuring that the experimental and control groups were homogeneous, and that the data distribution did not differ significantly. This method ensured that each cluster had an equal chance of selection.

Table 1. Non-equivalent control group design

Class	Pre-test	Treatment	Post-test
Experiment	O_1	X_1	O_2
Control	O_1	X_2	O_2

Description:
O_1 = Data from the evaluation of critical thinking and collaboration skills before treatment
O_2 = Data from the evaluation of critical thinking and collaboration skills after treatment
X_1 = Learning using e-worksheet renewable energy on STEM-project based learning
X_2 = Learning using conventional learning models

Data collection was carried out using two types of instruments: test instruments to measure critical thinking skills and a questionnaire to assess collaboration skills. The validity of these instruments was tested prior to their use to ensure that they were relevant for measuring the intended learning outcomes. The validity of the test items was evaluated using the Aiken V formula, with a valid coefficient greater than 0.8 indicating high validity. These steps ensure that the tools used in the study are reliable for measuring the desired competencies. The test and questionnaire instruments were supported by an assessment rubric specifically designed to measure critical thinking and collaboration skills. Indicators of critical thinking skills are: (1) analyze facts based on problems, (2) formulate problems, (3) choose logical arguments based on relevant information, and (4) make conclusions. While the indicators of collaboration skills are: (1) contribute actively and effectively, (2) work together productively, (3) take responsibility, (4) respect other members, and (5) adapt to various roles.

The electronic worksheets used in this study are accessible via the following URL: https://www.liveworksheets.com/w/id/fisika/7740747. The design of the e-worksheet was created using Canva, a tool chosen for its intuitive and user-friendly interface, making it accessible even to users without prior design experience. The design aims to be visually appealing and contemporary. The e-worksheet cover design is shown in Figure 1. It was launched using Liveworksheets, a platform that allows students to access the e-worksheet through a link, ensuring compatibility across various operating systems and devices. Furthermore, by utilizing Liveworksheets, the e-worksheet integrates the necessary learning videos, facilitating students' understanding of the learning process. The developed e-worksheet includes the following sections: cover page, preface, table of contents, instructions for use, student identity, a description of learning activities with apperception, a video demonstrating the steps for creating a simple waterwheel project, and an evaluation.

The e-worksheet was structured using the STEM-PjBL syntax, which includes five key components: reflection, research, discovery, application, and communication. The learning activities in this study were conducted over three sessions. The first session introduced various forms of energy, energy transformations, and renewable energy sources used in Indonesia. The second session focused on creating a simple waterwheel project, an example of renewable energy that can be utilized as an alternative energy source. In the third session, each group presented their successfully constructed waterwheel project and concluded by discussing the material they had learned.

Figure 1. Display e-worksheet cover

The data collected from the pretest and posttest were analyzed using statistical software (SPSS version 27.0 for Windows). A normality test was conducted using the Shapiro-Wilk test, appropriate for small sample sizes. If the p-value (significance level) was greater than 0.05, the data were considered normally distributed; otherwise, the data were deemed not normally distributed. After checking for normality, a homogeneity test was conducted to evaluate whether the variances in critical thinking and collaboration skills were equal across the groups. If the homogeneity test result yielded a p-value greater than 0.05, the data were considered homogeneous. Subsequently, a General Linear Model (GLM) test was performed to determine whether there was a statistically significant difference in student learning outcomes before and after the treatment.

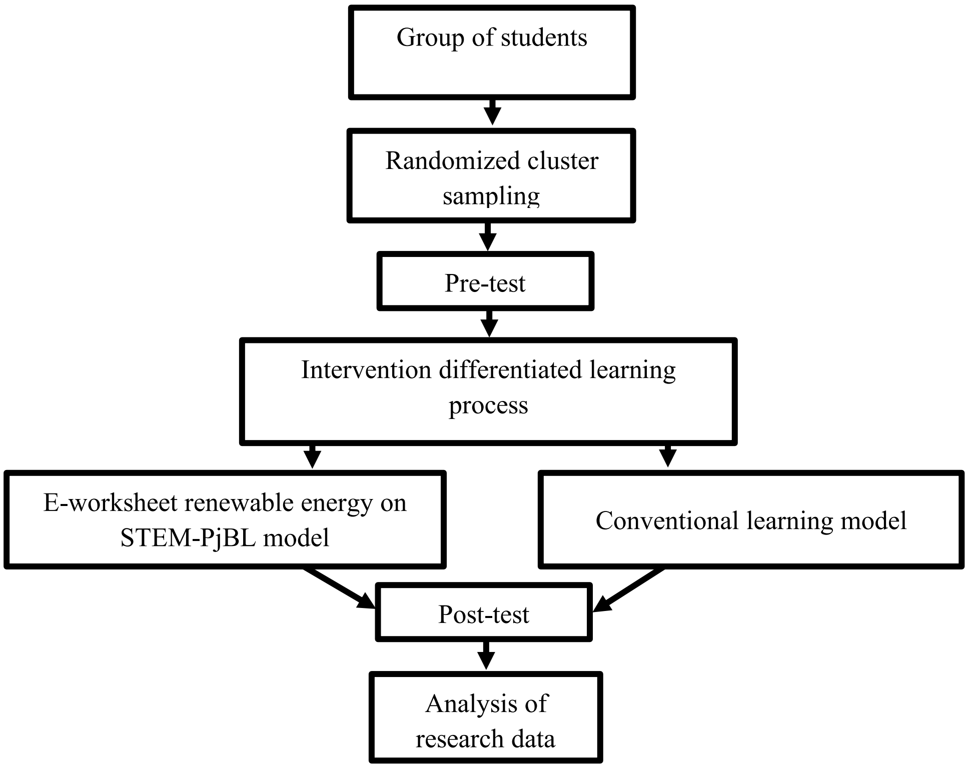

Figure 2. Research design and procedure for implementing STEM PjBL

The critical thinking skills test instrument and the collaboration skills questionnaire were validated by two expert validators, who were both physics education lecturers and two physics teachers. The assessment of the instruments included the evaluation of content validity, language feasibility, and item construction. Based on the validation results, the experts concluded that both the test and questionnaire instruments were appropriate for measuring the targeted skills in critical thinking and collaboration.

$$N - Gain = \frac{(S_{post} - S_{pre})}{(S_{max} - S_{pre})} \quad (1)$$

Description:
S_{post} = post-test scores for each student
S_{pre} = pre-test scores for each student
S_{max} = maximum score

The result of the calculation of the gain score (N-Gain) can be classified according to the criteria listed in Table 2.

Table 2. N-Gain score classification criteria for learning improvement levels

Interval	Category
0.70 < N-Gain	High
0.30 ≤ N-Gain ≤ 0.70	Medium
N-Gain < 0.30	Low

The N-Gain test was conducted using Microsoft Excel. Additionally, the effectiveness of the intervention was calculated using Cohen's d formula to measure the degree of impact the treatment had on the sample size. Cohen's d value provided an estimate of the effect size, indicating how strong the treatment's effect was on improving students' critical thinking and collaboration skills.

III. RESULTS AND DISCUSSION

The pretest and posttest responses from the students were collected and scored according to the established scoring rubric. The total pretest and posttest scores for each student were then analyzed using SPSS version 27.0 for Windows. Inferential data analysis was employed to determine the impact of the renewable energy e-worksheet on STEM-PjBL by comparing students' pre-test and post-test scores. The N-Gain test equation was used to evaluate the results. The findings are presented by assessing the pre-test and post-test scores, with specific attention to the indicators of critical thinking and collaboration skills. Figure 3 illustrates the mean scores for critical thinking and collaboration skills across the experimental and control classes.

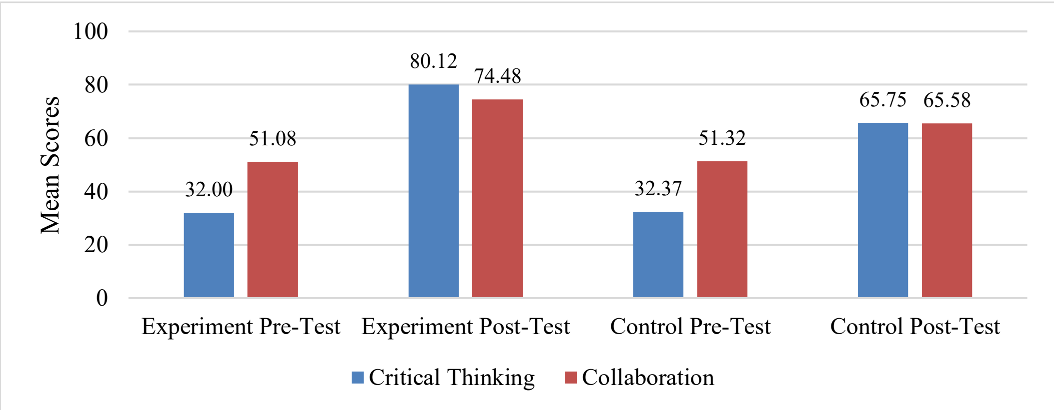

Figure 3. Mean students' scores on critical thinking skill and collaboration skills

The increase in post-test scores obtained by students is observable through the scatter diagram. As shown in Figure 3, there was a significant increase in the post-test scores compared to the pre-test scores for each variable. This improvement in learning outcomes aligns with findings from previous studies, which suggest that STEM-PjBL enhances students' critical thinking and collaboration skills. For instance, a study by Nisah et al. (2024) found that STEM-PjBL significantly improved students' critical thinking skills, while Yanti et al. (2023) noted that such learning motivated students to develop their collaboration skills. Table 3 displays the results of the normality test based on the Shapiro-Wilk test, which was conducted due to the small sample size (fewer than 50 respondents per class).

Table 3. Result of pre-test and post-test by shapiro-wilk normality test

Variable	Test	Class	Stat.	df	Sig.
Critical thinking skill	Pre-Test	Experiment	0.981	25	0.905
		control	0.971	25	0.678
	Post-Test	Experiment	0.936	25	0.118
		control	0.977	25	0.825
Collaboration skill	Pre-Test	Experiment	0.966	25	0.522
		control	0.975	25	0.766
	Post-test	Experiment	0.959	25	0.403
		control	0.952	25	0.284

Based on Table 3, which shows the results of the normality test conducted using the Shapiro-Wilk test, all data have a significance value greater than 0.05, suggesting that the pre-test and post-test data for both critical thinking skills and collaboration skills are normally distributed. Following the normality test, a homogeneity test was conducted to determine whether the variances of critical thinking and collaboration skills were homogeneous across the experimental and control classes. Levene's test was used for this analysis, and the results can be found in Table 4.

Table 4. Homogeneity test results in pre-test and post-test by Levene's test

Variable	Test	Levene's Test	df1	df2	Sig.
Critical thinking skills	Pre-test	0.070	1	48	0.793
	Post-test	2.952	1	48	0.092
Collaboration skills	Pre-test	0.073	1	48	0.788
	Post-test	0.007	1	48	0.936

From Table 4, it is evident that the variables for critical thinking skills and collaboration skills show a significance value greater than 0.05. Therefore, it can be concluded that the pre-test and post-test data for both skills come from samples with the same population, indicating homogeneity. After the normality and homogeneity tests were conducted on the critical thinking and collaboration skills scores, the N-Gain test data were analyzed to determine the improvement category and the effectiveness of using the renewable energy e-worksheet in STEM project-based learning. The results of the N-Gain calculation, as shown in Table 5, demonstrate that the use of the e-worksheet improved both critical thinking and collaboration skills in students.

Table 5. N-Gain analysis and improvement levels of students' critical thinking and collaboration skills

Variable	Class	N-Gain score	Category
Critical thinking skills	Experiment	0.72	High
	control	0.52	Medium
Collaboration skills	Experiment	0.75	High
	control	0.46	Medium

Based on the N-Gain results in Table 5, it is evident that the use of the renewable energy e-worksheet in STEM-PjBL significantly improved students' critical thinking and collaboration skills. The N-Gain value for the experimental class using the e-worksheet is higher than the value for the control class, which used conventional learning methods. Furthermore, the effectiveness of improving students' critical thinking and collaboration skills after using the e-worksheet was calculated using Cohen's d-effect size formula. The effect size of 0.275 falls into the high category, indicating a significant impact of the intervention. This calculation demonstrates that learning with STEM-PjBL through e-worksheets effectively enhances students' critical thinking and collaboration skills. The marked increase in posttest scores compared to pretest scores reflects that the e-worksheet, based on STEM project-based learning, successfully optimized the learning process and provided a deeper learning experience for the students.

The results of this study confirm that integrating STEM-PjBL with digital e-worksheets offers a significant advantage in cultivating critical thinking and collaboration skills among high school students. The observed high N-Gain scores in the experimental group 0.72 for critical thinking and 0.75 for collaboration demonstrate that structured, interdisciplinary, and context-driven learning environments can enhance cognitive engagement more effectively than conventional methods. These findings support prior research suggesting that PjBL, especially when implemented within a STEM framework, encourages students to solve real-world problems while applying conceptual knowledge across disciplines. In particular, the use of a renewable energy theme and a tangible project (a simple waterwheel) provided an authentic learning context that made abstract physics concepts more concrete, relevant, and engaging for students. This setting not only facilitated knowledge construction but also promoted active student involvement through inquiry, reflection, and discussion.

The implementation of STEM-PjBL further provides students with meaningful opportunities to collaboratively generate ideas (Bulu & Tanggur, 2021), solve problems in teams, and reflect on their thought processes elements essential for cultivating both critical thinking and communication skills. As students worked in groups to complete their renewable energy projects, they developed interpersonal skills such as responsibility, adaptability, and respect for others' perspectives, which are essential in both academic and real-world professional environments. The instructional design of the e-worksheet, which incorporated phases of reflection, exploration, creation, and communication, supported a dynamic learning process where students were encouraged to think analytically and work collectively toward common goals. This aligns with Rizki et al. (2024), who argue that project-based models with real-world relevance not only improve student learning outcomes but also deepen their engagement with scientific practices.

The structured group activities in this study helped to create a collaborative classroom culture, which in turn reinforced the acquisition of complex problem-solving abilities.

This research makes a significant contribution to physics education by demonstrating how STEM-PjBL models, when supported by digital tools such as e-worksheets, can bridge the gap between theoretical knowledge and practical application. It provides a viable model for 21st-century physics instruction that emphasizes conceptual understanding, interdisciplinary thinking, and collaborative skill development. The study's findings highlight the potential of contextualized, hands-on projects to not only enhance academic achievement but also to foster skills that are critical for scientific literacy and lifelong learning. As physics education continues to evolve, integrating meaningful projects that are relevant to sustainability and real-world challenges such as renewable energy can play a central role in preparing students to become informed and responsible citizens. Consequently, this model serves as a replicable, evidence-based framework for educators aiming to innovate their teaching practices in line with current educational goals and future societal needs.

IV. CONCLUSION AND SUGGESTION

This study demonstrated that the integration of a renewable energy e-worksheet within a STEM-PjBL framework significantly improved students' critical thinking and collaboration skills. The experimental group showed high improvement levels, with N-Gain scores of 0.72 for critical thinking and 0.75 for collaboration, while the control group exhibited only moderate gains. These findings support the effectiveness of the developed e-worksheet in facilitating deeper cognitive engagement and fostering 21st-century competencies through student-centered and interdisciplinary learning activities.

Despite these promising findings, the study has several limitations. It was confined to a single topic renewable energy and conducted in one school with a relatively small sample size. The observed effectiveness may also have been influenced by factors such as students limited prior exposure to project-based learning, variation in teachers' digital pedagogical competencies, and the dependence on stable internet connectivity throughout the learning process. Future research should explore the broader application of STEM-PjBL e-worksheets across a wider range of physics topics, in diverse educational settings, and with larger, more heterogeneous student populations. Additionally, further studies could examine the comparative effects of different types of renewable energy projects and evaluate the long-term retention of critical thinking and collaboration skills. Overall, this study contributes to physics education by providing a validated, interactive, and technology-integrated instructional model that addresses key learning challenges, enhances student engagement, promotes collaborative problem-solving, and prepares learners to navigate complex real-world issues in science and technology.

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