GeoScienceEd *7(2) (2026)*

Jurnal Pendidikan, Sains, Geologi, dan Geofisika

http://jpfis.unram.ac.id/index.php/GeoScienceEdu/index

Effectiveness of PjBL Assisted by e-LKPD DTRE on Critical Thinking and Learning Motivation

Khairunnisah[1*], Lina Aviyanti[1], Iin Suminar[1]

[1] Physics Education, Faculty of Mathematics and Natural Sciences Education Universitas Pendidikan Indonesia, Bandung, Indonesia

DOI: https://doi.org/10.29303/goescienceed.v7i2.1891

Article Info:
Received : April, 25 2025
Revised : April, 30 2025
Accepted : May, 09 2026
Published : May, 17 2026

Correspondence:

Khairunnisah

Phone:

Abstract: This study examines the effectiveness of Project-Based Learning (PjBL) assisted by e-LKPD Design Thinking on Renewable Energy (DTRE) in improving students' critical thinking skills and learning motivation. A quasi-experimental design with a non-equivalent control group was employed. The sample consisted of 35 students in the experimental class (PjBL assisted by e-LKPD DTRE) and 34 students in the control class (PjBL with conventional worksheets) at a senior high school in Bandung. Data were collected using a validated critical thinking test and a learning motivation questionnaire and analyzed using normalized gain (N-gain) and non-parametric statistical tests. The results showed that both groups improved; however, the experimental class achieved a higher N-gain (0.42, moderate) than the control class (0.28, low). A significant difference was found between groups ($p < .001$) with a moderate effect size ($r = 0.443$). The highest improvement occurred in the elementary clarification indicator (N-gain = 0.54), indicating that structured project activities supported students in identifying and explaining problems more systematically. Learning motivation was categorized as moderate (66.09%), with the highest score in the relevance dimension (72.22%), suggesting that the learning approach helped connect concepts with real-life contexts. In conclusion, integrating e-LKPD DTRE within PjBL effectively enhances students' critical thinking skills and supports meaningful and contextual learning, with potential for further refinement to strengthen students' motivation.

Keywords: Critical Thinking; Design Thinking; E-LKPD; Project-Based Learning; Renewable Energy

Citation: Khairunnisah, K., Aviyanti, L., & Suminar, I. (2026). Effectiveness of PjBL Assisted by e-LKPD DTRE on Critical Thinking and Learning Motivation. *Jurnal Pendidikan, Sains, Geologi, Dan Geofisika (GeoScienceEd Journal)*, *7*(2), 1414–1423. https://doi.org/10.29303/goescienceed.v7i2.1891

Introduction

The development of 21st-century competencies has become a main purpose of modern education systems in preparing students to face complex global challenges. These competencies include critical thinking, communication, collaboration, and creativity, which are aligned with the four pillars of education: learning to know, learning to do, learning to be, and learning to live together (Hartono et al., 2022). Among these competencies, critical thinking plays a crucial role in enabling students to analyze information, evaluate evidence, and make reasoned decisions in various contexts. Critical thinking is widely recognized as a higher-order thinking skill that supports analytical reasoning, problem-solving, and decision-making processes.

According to Ennis (2011), critical thinking is reasonable and reflective thinking focused on deciding what to believe or do. Similarly, Scriven and Paul (1987) as well as Angelo (1995) emphasize that critical thinking involves active processes of conceptualization, application, analysis, synthesis, and evaluation. These cognitive processes are essential for meaningful learning, particularly in science education, where

Email: khairunnisah@upi.edu

students are required to understand abstract concepts and apply them to real-world situations (Octafianellis et al., 2021; Ariadila et al., 2023). In addition, prior studies have shown that critical thinking is closely related to students' ability to construct knowledge and solve complex problems effectively (Halpern, 2014; Facione, 2015)

Despite its crucial role, students' critical thinking skills remain relatively low. Several studies indicate that this issue is closely related to the dominance of teacher-centered learning practices and an overemphasis on procedural outcomes rather than deep conceptual understanding (Illahi, 2023; Cacik & Widiyanti, 2024; Wilson & Defianty, 2024). This condition is further reflected in international assessment results from the Programme for International Student Assessment, which show that students' performance in mathematics, reading, and science is still below the OECD average. In the 2022 PISA results, Indonesia scored 366 in mathematics, 359 in reading, and 383 in science, compared to the OECD averages of 472, 476, and 485, respectively (OECD, 2023). These results suggest that students still face difficulties in higher-order thinking tasks, including analysis, evaluation, and reasoning, which are essential components of critical thinking in physics learning.

Project-Based Learning (PjBL) has been widely proposed as an effective approach to foster critical thinking skills. This model engages students in authentic learning experiences by involving them in problem identification, solution design, and reflective evaluation processes (Markula & Aksela, 2022). In addition, the integration of design thinking into PjBL has been shown to enhance students' analytical and critical thinking abilities through iterative processes such as problem exploration, idea generation, prototyping, and evaluation (Anggraini et al., 2024). Design thinking adopts a human-centered approach consisting of stages including empathize, define, ideate, prototype, and test, which support students in developing deeper understanding and innovative problem-solving skills (Razzouk & Shute, 2012; Maknuunah et al., 2021).

However, the effectiveness of Project-Based Learning (PjBL) is highly depends on the quality of instructional materials used during the learning process. Preliminary findings from a senior high school in Bandung, obtained through classroom observation, interviews, and document analysis, indicate that although PjBL has been implemented, students' critical thinking skills have not yet developed optimally. This finding is further supported by a preliminary assessment of students' critical thinking skills conducted using a validated instrument administered to senior high school students in Bandung. The results indicate that students' critical thinking skills are generally at a moderate level, with 72.8% of students categorized as moderate, 16.6% as low, and only 10.6% reaching a high level. The Rasch model analysis revealed a mean student ability of +0.23 logit, equivalent to approximately 54% of the maximum score, which is still below the school's minimum mastery criterion (75). These results suggest that although students possess basic critical thinking abilities, they still experience difficulties in performing higher-order cognitive processes such as in-depth analysis, argument evaluation, and drawing well-supported conclusions.

More detailed observations from classroom practices indicate that learning activities are still dominated by teacher explanations. Although PjBL has been introduced, its implementation has not fully followed the intended syntax, resulting in limited opportunities for students to engage in authentic project-based inquiry. For instance, students tended to complete tasks by directly following given procedures without questioning the underlying concepts or exploring alternative solutions. In addition, the instructional materials used in the classroom, particularly student worksheets, tend to be procedural and conventional, focusing on step-by-step completion rather than encouraging reflective and analytical thinking. The worksheets resemble "cookbook" activities, where students are guided through fixed steps, leaving minimal space for reasoning, interpretation, or independent decision-making. As a result, students often struggle when asked to interpret data, justify their answers, or relate concepts to real-world contexts.

This condition is further reflected in students' responses during interviews, where several students reported that they were accustomed to completing tasks based on instructions but felt uncertain when required to explain their reasoning or draw conclusions independently. As a result, students are more likely to follow instructions mechanically rather than engage in deeper reasoning processes.

These findings highlight a gap between the implementation of PjBL and its expected outcomes in fostering critical thinking skills. Therefore, there is a need for more structured and interactive learning materials that can better support the development of students' higher-order thinking skills within the PjBL framework. To address these limitations, the use of electronic student worksheets (e-LKPD) offers a promising alternative. Compared to conventional worksheets, e-LKPD provides interactive features, multimedia integration, and flexible access, which can enhance student engagement and support deeper cognitive processing (Andriana et al., 2022; Agustin et al., 2025). The integration of e-LKPD within PjBL can serve as a structured guide that facilitates inquiry-based learning and supports the development of critical thinking skills in a more systematic manner.

Although previous studies have demonstrated the effectiveness of Project-Based Learning, design thinking, and digital learning materials in improving students' higher-order thinking skills, most of these studies have examined these components separately rather than as an integrated instructional approach. (Putra et al., 2021; Rianto et al., 2023; Safitri et al., 2024). As a result, there is still limited empirical evidence on how the integration of these elements can collectively enhance students' critical thinking skills, particularly in the context of renewable energy learning.

Therefore, this study aims to examine the effectiveness of Project-Based Learning assisted by an e-LKPD based on Design Thinking on Renewable Energy (DTRE), specifically focusing on wind energy (PLTB), in improving students' critical thinking skills. This integrated approach is expected to provide a more meaningful and structured learning experience that promotes higher-order thinking skills in science education.

Method

This study employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. Both groups were administered a pretest and posttest; however, the experimental group was treated using Project-Based Learning (PjBL) assisted by e-LKPD DTRE, whereas the control group received instruction through PjBL supported by conventional worksheets, as presented in Table 1.

Table 1. Research design

Group	Pretest	Treatment	Posttest
Experimental Group	O_1	X_1	O_2
Control Group	O_1	X_2	O_2

The participants of this study were tenth-grade students from a public senior high school in Bandung. A purposive sampling technique was used to select two classes that had not previously studied renewable energy materials and had access to digital devices. The final sample consisted of 35 students in the experimental group and 34 students in the control group. The instrument used to measure students' critical thinking skills was a test consisting of 10 essay items developed based on Ennis' critical thinking framework. The distribution of items across the five indicators is presented in Table 2.

Each item was scored using an analytical rubric with a scale of 1–4, resulting in a maximum total score of 40, which was then converted into a scale of 1–100. Prior to its implementation, the instrument was validated by experts and empirically tested through a pilot study involving 31 students using Rasch model analysis with the assistance of Winsteps software. The results indicated that all items met the fit criteria (0.5 < MNSQ < 1.5), with most items categorized as very fit. The instrument also demonstrated good reliability (Cronbach's alpha = 0.85; person reliability = 0.84; item reliability = 0.77), indicating that it was valid and reliable for measuring students' critical thinking skills.

Tabel 2. Distribution of critical thinking test items based on indicators

No.	Critical Thinking Indicator	Item Number	Number of Item
1	Elementary clarification	1, 3	2
2	Basic support	4, 7	2
3	Inference	5, 8	2
4	Advanced Clarification	2,9	2
5	Strategies and tactics	6, 10	2
Total			**10**

Students' learning motivation was measured using a questionnaire adapted from the Instructional Materials Motivation Survey (IMMS) developed by John M. Keller based on the ARCS model, which includes four dimensions: attention, relevance, confidence, and satisfaction. The questionnaire consisted of 16 items, including both positive and negative statements, with each dimension proportionally represented to capture students' responses to the implemented learning process.

The learning intervention was implemented using e-LKPD DTRE integrated within the PjBL framework in the experimental class, while the control class utilized conventional worksheets. The e-LKPD DTRE was developed using a digital platform (e.g., Google Sites and Wizer.me) and designed to facilitate interactive and structured learning activities. It integrates the stages of design thinking, namely empathize, define, ideate, prototype, and test, within the Project-Based Learning framework. The learning content focuses on renewable energy, particularly the analysis of energy crisis issues and the development of solutions in the form of a mini wind power plant (PLTB) prototype.

The implementation of the learning intervention was conducted over four meetings, each lasting approximately 120 minutes. In the first meeting, students engaged in the empathize stage by exploring contextual problems related to the energy crisis. In the second meeting, students proceeded to the define and ideate stages through case analysis and virtual simulations using PhET. In the third meeting, students carried out the prototype stage by developing a mini

PLTB prototype. In the fourth meeting, students conducted the test stage by measuring electrical output, analyzing data, and presenting results.

Data analysis was conducted using descriptive and inferential statistics. The improvement in students' critical thinking skills was measured using normalized gain (N-gain), which was categorized according to Hake (1998) into high, medium, and low levels. This measure was used to capture the relative improvement of students by taking into account both pretest and posttest scores, so that the comparison between groups becomes more meaningful. To determine the significance of differences, non-parametric tests were applied due to the non-normal distribution of data, including the Wilcoxon signed-rank test and the Mann–Whitney U test. The selection of non-parametric tests was based on the characteristics of the data, which did not meet the assumption of normality, making these tests more appropriate for analyzing differences within and between groups without relying on parametric assumptions. Effect size was also calculated to determine the magnitude of the treatment effect, since statistical significance alone does not fully reflect how substantial the impact of the intervention is in practice.

Result and Discussion

The pretest results indicate that the experimental and control groups had comparable initial levels of critical thinking skills. As shown in Table 3, the experimental group obtained a mean score of 48.93 (SD = 9.18), while the control group achieved a mean score of 46.32 (SD = 7.13). The relatively small difference between the two groups suggests that both groups started from a similar initial levels of critical thinking skills. This initial equivalence is important in a quasi-experimental design, as it ensures that any subsequent differences in learning outcomes can be more confidently attributed to the intervention rather than pre-existing differences.

Table 3. Descriptive Statistics of Pretest Scores

Group	N	Minimum	Maximum	Mean	SD
Experimental	35	32.50	55.00	48.93	9.18
Control	34	30.00	57.50	46.32	7.13

After the intervention, both groups showed improvement in critical thinking skills. However, the experimental group demonstrated a more substantial increase. As presented in Table 4, the experimental group's mean score increased from 48.93 to 70.29, while the control group increased from 46.32 to 61.25. The normalized gain (N-gain) analysis further confirmed this difference, with the experimental group achieving a N-gain of 0.42 (moderate category) compared to 0.28 (low to moderate) in the control group. Despite the higher improvement, the gain in the experimental group remained within the moderate category. This may be attributed to several factors, such as the relatively short duration of the intervention, students' initial unfamiliarity with Project-Based Learning and design thinking processes, and the limited time for deeper reflection and iterative problem-solving.

In addition, the development of higher-order thinking skills, such as inference and advanced clarification, generally requires sustained practice and longer exposure to cognitively demanding tasks. These findings indicate that the integration of e-LKPD DTRE within Project-Based Learning contributes to a meaningful, yet still developing, enhancement of students' critical thinking skills.

Table 4. Pretest–Posttest Comparison and N-Gain

Group	Pretest Mean	Posttest Mean	N-gain	Category
Experimental	48.93	70.29	0.42	Moderate
Control	46.32	61.25	0.28	Low-Moderate

The difference between groups was statistically significant ($p < .001$) with a moderate effect size ($r = 0.443$), indicating that the intervention had a meaningful impact on students' learning outcomes. This finding suggests that while Project-Based Learning (PjBL) contributes to improving critical thinking skills, its integration with e-LKPD Design Thinking on Renewable Energy (DTRE) provides additional cognitive support that enhances the learning process more effectively. The well-organized and phased design of the e-LKPD is likely to foster deeper cognitive processing, as it directs learners through identifying problems, generating ideas, constructing solutions, and reflecting on their learning. These results align with earlier research suggesting that systematically designed of digital learning materials can promote critical thinking skills (Ennis, 2011; Hartono et al., 2022; Zulkarnaen at al., 2025). A more detailed examination of learning outcomes is presented in Table

5, which shows the N-gain scores across critical thinking indicators. Overall, the experimental group consistently outperformed the control group in all indicators.

The highest improvements in the experimental group were observed in elementary clarification (0.54) and basic support (0.53). This indicates that students became more capable of identifying problems, interpreting information, and providing evidence-based reasoning. These improvements can be linked to the design thinking stages embedded in the e-LKPD DTRE. In particular, elementary clarification was developed through the *define*, *ideate*, and *test* stages, where students were required to formulate problem statements, propose solution ideas, and compare prototype performance. These improvements are closely related to the structured activities within e-LKPD DTRE, which guide students through problem identification and idea formulation stages

Table 5. N-Gain Based on Critical Thinking Indicators

Indicator	Experimental	Control
Elementary clarification	0.54	0.38
Basic support	0.53	0.40
Inference	0.32	0.15
Advanced clarification	0.35	0.14
Strategies and tactics	0.37	0.33

In contrast, the lowest improvement in the experimental group was found in the inference indicator, with an N-gain value of 0.32 within the moderate category. Meanwhile, the control group demonstrated lower improvements, particularly in inference (0.15) and advanced clarification (0.14), which remained at a low level. Although inference was facilitated across several stages, such as empathize, define, ideate, and test, the moderate gain suggests that students still require more time and repeated practice to develop the ability to draw conclusions from data and establish causal relationships. This pattern implies that students faced challenges in developing critical thinking skills without adequate scaffolding, which were more effectively facilitated in the experimental class. These findings are aligned with previous research indicating that complex cognitive processes, such as inference and advanced clarification, require guided learning experiences and iterative practice (Rachmawati & Wiyatmo, 2025; Meirawati et al., 2025).

A similar tendency is observed in advanced clarification (0.35), which was mainly trained in the define stage through activities that required students to construct and justify conceptual understanding based on simulation results. The relatively moderate improvement indicates that the ability to provide deeper explanations develops gradually and depends on sustained engagement with conceptually demanding tasks.

Meanwhile, the strategies and tactics indicator (0.37) was fostered through the ideate and prototype stages, where students planned project implementation and adjusted their approach during the prototyping process. These activities encouraged students to think strategically and adapt their decisions based on emerging constraints during the project. The improvement pattern in the experimental group is further illustrated in Figure 1, which shows increases across all critical thinking indicators from pretest to posttest. This finding suggests that the integration of design thinking stages within Project-Based Learning provides structured opportunities for students to engage in systematic and meaningful problem-solving processes.

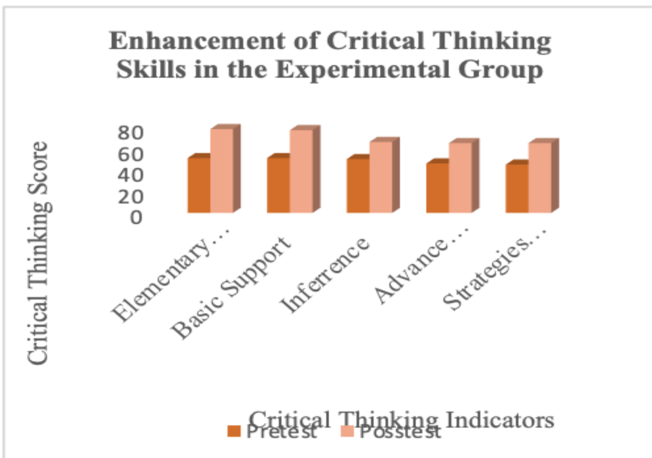

Figure 1. Pretest-Posttest score based on critical thinking indicators in experimental class

The improvement observed in both groups also indicates that Project-Based Learning itself plays an important role in fostering critical thinking. This aligns with previous studies showing that PjBL promotes active learning through problem-solving, collaboration, and reflection (Widyastuti, 2022; Dewi et al., 2025). Through these processes, students are encouraged to analyze problems, evaluate information, and construct solutions, which are essential components of critical thinking (Gandi et al., 2021; Sun et al., 2024; Apriliyanti et al., 2025). However, the higher improvement in the experimental group indicates that the addition of e-LKPD DTRE plays a crucial role in strengthening these processes by providing structured and sequential learning support. Unlike conventional worksheets, the e-LKPD used in this study provides structured and sequential learning stages based on design thinking, which guide students in analyzing problems, generating ideas, testing solutions, and reflecting on their learning. This structured scaffolding promotes deeper cognitive processes, particularly in reasoning, analysis, and evidence-based decision-making (Andriana et al., 2022; Agustin et al., 2025).

Interestingly, the relatively similar N-gain values observed in the strategies and tactics indicator between the experimental (0.37) and control groups (0.33) suggest that this skill is inherently developed through the PjBL framework itself. In both groups, students were actively involved in planning, organizing, and executing project activities, which inherently require them to determine appropriate actions and collaborate with peers. These processes naturally foster strategic thinking and decision-making skills, even without additional instructional support (Zulkarnaen at al., 2025).

This result implies that the development of strategies and tactics is less dependent on the presence of supplementary learning materials, since it is intrinsically embedded within the core framework of PjBL. This interpretation is reinforced by the findings of Isro et al. (2021), which show that students involved in PjBL-STEM learning tend to achieve very high performance in strategy and tactics aspects, particularly in deciding actions and interacting within groups. Through repeated collaborative activities, students are trained to negotiate ideas, determine appropriate solutions, and adjust their strategies based on group discussions. As a result, the development of this indicator becomes strongly embedded in the learning model itself rather than being dependent on supplementary instructional materials.

In addition, previous research using Rasch analysis highlights that critical thinking skills, including strategic decision-making, develop through continuous practice and iterative learning experiences (Aviyanti et al., 2024). This suggests that the relatively similar improvement between groups in this indicator may reflect the cumulative effect of repeated engagement in project-based activities rather than the specific contribution of e-LKPD DTRE. Thus, although the e-LKPD contributes to the improvement of several indicators of students' critical thinking skills, its impact on the strategies and tactics indicator remains relatively limited, as this component has already been strongly emphasized within the PjBL framework. Furthermore, a meta-analysis study by Tafakur et al. (2023) confirms that Project-Based Learning has a consistent positive effect on students' critical thinking skills, particularly in aspects related to problem-solving and decision-making. This suggests that the relatively small difference between groups in this indicator is likely due to the dominant influence of the PjBL model itself, rather than the added effect of e-LKPD DTRE.

The effectiveness of e-LKPD DTRE can also be explained through its integration of design thinking stages. Activities such as empathizing with real-world energy issues, defining problems, generating ideas, developing prototypes, and testing solutions provide students with opportunities to engage in iterative and reflective thinking processes. These processes are essential in developing critical thinking, as they require students to analyze information, evaluate alternatives, and justify their decisions. This finding is aligned with previous studies indicating that the integration of project-based learning, design thinking, and digital learning materials enhances deeper cognitive engagement and promotes critical thinking skills (Rachmawati & Wiyatmo, 2025; Meirawati et al., 2025).

Furthermore, the use of contextual problems related to renewable energy contributes to meaningful learning experiences. By connecting learning content to real-world issues, students are encouraged to apply their knowledge in practical contexts, which strengthens their analytical and reasoning abilities (Octafianellis et al., 2021; Ariadila et al., 2023; Zulkarnaen at al., 2025). This aligns with previous findings that contextual and problem-based learning environments significantly support the development of critical thinking skills in science education (Gandi et al., 2021; Putra et al., 2021; Safitri et al., 2024).

In addition to cognitive outcomes, this study also examined students' learning motivation based on the ARCS model. The results indicate that students' overall motivation was in the moderate category (66.09%), suggesting that the learning intervention was able to engage students, although not yet optimally. A more detailed analysis of motivation across dimensions is presented in Figure 2, which illustrates the distribution of students' motivation in terms of attention, relevance, confidence, and satisfaction.

The relevance dimension achieved the highest percentage (72.22%), indicating that students were able to perceive a strong connection between the learning content and real-life contexts, particularly in relation to renewable energy issues. This finding suggests that the integration of contextual problems, such as energy crises and the development of wind power prototypes, successfully enhanced the meaningfulness of learning. When students recognize the applicability of knowledge in real-world situations, they tend to be more engaged and motivated to participate actively in the learning process. This result is consistent with previous studies highlighting that contextual and project-based learning environments improve students' engagement and perceived value of learning (Ainurridho et al., 2021; Dewi et al., 2025; Palangi et al., 2025), and is also aligned with the ARCS model which emphasizes the importance of relevance in connecting learning materials with students' real-life experiences (Keller, 2004; Ramadhani, 2022; Sarıkoç & Ozerbaş, 2024).

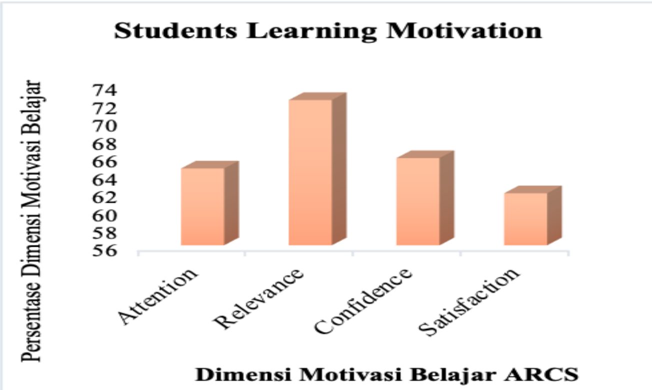

Figure 2. Percentage of Students' Learning Motivation Across ARCS Dimensions

The confidence dimension (65.74%) indicates that students experienced a moderate level of self-efficacy during the learning process. This suggests that project-based activities, such as designing and developing prototypes, provided opportunities for students to build confidence through hands-on experiences. This finding is aligned with previous studies indicating that active engagement in project-based learning can enhance students' self-efficacy and intrinsic motivation (Dewi et al., 2025). However, the moderate score also implies that not all students felt equally confident, which may be influenced by factors such as task complexity, time constraints, and challenges in group collaboration. This condition is in line with findings that the effectiveness of PjBL is influenced by project design, student readiness, and the level of instructional support provided by the teacher (Dewi et al., 2025; Sarıkoç & Ozerbaş, 2024). This finding highlights the importance of providing sufficient scaffolding and guidance during project implementation to support students with varying levels of readiness.

Meanwhile, the attention dimension (64.58%) reflects that the learning activities were able to attract students' interest, although not consistently across all participants. The use of interactive activities such as discussions, simulations, and prototype development contributed to increased engagement. This finding supports previous research stating that elements of PjBL, such as authentic problems and active inquiry, can enhance students' attention and engagement (Al-Kamzari & Alias, 2023; Sarıkoç & Ozerbaş, 2024). However, the moderate level suggests that certain aspects, such as complex instructions or technical constraints, may have reduced students' focus during the learning process. Similar challenges have been reported in studies highlighting that technical limitations and the complexity of digital learning media can affect students' engagement (Wahyuniyati et al., 2025). This indicates that while PjBL combined with digital tools has the potential to enhance engagement, user-friendly instructional design is required to maintain students' attention effectively.

The satisfaction dimension recorded the lowest percentage (61.81%), indicating that students' sense of achievement and satisfaction with the learning experience was not yet optimal. Although many students reported enjoying the project-based activities, some experienced challenges related to task difficulty, limited time, and suboptimal project outcomes, which may have influenced their level of satisfaction. This finding is aligned with previous research indicating that students' satisfaction in project-based learning is closely related to their success in completing tasks and producing meaningful outcomes (Palennari & Bahri, 2025; Sarıkoç & Ozerbaş, 2024). This finding suggests that emotional responses to learning are closely linked to students' perceived success and the quality of their learning experience.

Taken together, these results indicate that Project-Based Learning assisted by e-LKPD DTRE effectively supports students' learning motivation, particularly in enhancing the perceived relevance of learning. However, further optimization is still required in terms of instructional support, time management, and task design to improve students' confidence, attention, and satisfaction more evenly.

Overall, these findings demonstrate that Project-Based Learning (PjBL) not only provides a strong foundation for developing students' critical thinking skills but also supports students' learning motivation when implemented with structured digital scaffolding such as e-LKPD DTRE. The integration of project-based learning, design thinking processes, and digital worksheets creates a learning environment that is not only active and student-centered but also cognitively demanding and reflective. This combination enables students to engage more deeply in problem-solving processes while simultaneously perceiving the relevance of learning to real-world contexts, which is essential for sustaining motivation.

From a cognitive perspective, the structured stages embedded in e-LKPD DTRE facilitate higher-order thinking processes, particularly in reasoning, analysis, and evidence-based decision-making. From an affective perspective, the use of contextual and project-based activities strengthens students' perceived relevance of learning, which emerged as the most dominant motivational dimension. This indicates that meaningful learning occurs when cognitive engagement and motivational support are developed simultaneously rather than separately.

The findings of this study have several important implications. Practically, teachers are encouraged to integrate structured digital learning materials within project-based learning to support both critical thinking and student motivation. The use of design thinking stages can serve as an effective pedagogical framework to guide students through complex problem-solving tasks in a more systematic and reflective manner. Theoretically, this study contributes to the growing body of research emphasizing the importance of combining cognitive and motivational approaches in science education, particularly in the context of 21st-century learning.

Despite these promising findings, several limitations should be acknowledged. First, the study was conducted in a single school, which may limit the generalizability of the findings to broader educational settings. Second, the duration of the intervention was relatively short, which may not fully capture the long-term development of both critical thinking skills and learning motivation. Third, variations in students' initial abilities and group dynamics during project implementation may have influenced the outcomes, particularly in motivational aspects such as confidence and satisfaction.

Future research is therefore recommended to involve more diverse samples and extended implementation periods to examine the sustainability of both cognitive and motivational improvements. In addition, further studies may explore the integration of e-LKPD DTRE in different subject areas or investigate its impact on other 21st-century skills, such as collaboration, creativity, and problem-solving, to provide more comprehensive insights into its educational potential.

Conclusion

This study concludes that Project-Based Learning assisted by e-LKPD based on Design Thinking on Renewable Energy (DTRE) is effective in improving students' critical thinking skills and supporting their learning motivation. The experimental group demonstrated better improvement compared to the control group, indicating a meaningful impact of the intervention.

The findings also indicate that Project-Based Learning contributes to the development of fundamental critical thinking skills, particularly in problem identification and decision-making processes. However, the integration of e-LKPD DTRE plays a more substantial role in strengthening higher-level critical thinking skills, especially in inference and advanced clarification. This is achieved through structured, interactive, and reflective learning activities that guide students through systematic problem-solving processes.

This study provides empirical evidence that integrating PjBL, design thinking, and digital learning materials within a unified framework enhances students' cognitive engagement and critical thinking. In addition, students' learning motivation was found to be at a moderate level, with strong relevance to real-life contexts.

Overall, the integration of Project-Based Learning, design thinking, and e-LKPD creates a more meaningful, structured, and cognitively demanding learning environment. Therefore, this approach can be considered a promising alternative for improving students' critical thinking skills in science education, particularly in topics such as renewable energy that require contextual problem-solving and conceptual understanding. Future research is recommended to involve larger samples and longer implementation periods to further examine the consistency and broader applicability of this approach.

Acknowledgements

The authors sincerely express their gratitude to all faculty members of the Physics Education Departments at Universitas Pendidikan Indonesia for their valuable support and guidance throughout the research process.

References

Agustin, A. A. R., Saefullah, A., & Septiyant, R. F. (2025). Development of interactive e-LKPD based on socio-scientific issues on renewable energy material to facilitate students' critical thinking. Jurnal Pendidikan Fisika, 14(1), 36–45. https://doi.org/10.19184/jpf.v14i1.53695

Al-Kamzari, F., & Alias, N. (2025). A systematic literature review of project-based learning in secondary school physics: Theoretical foundations, design principles, and implementation strategies. Humanities and Social Sciences Communications, 12(1). https://doi.org/10.1057/s41599-025-04579-4

Andriana, E., Fauzany, P. S. D., & Alamsyah, T. P. (2022). 21st century multimedia innovation: The development of e-LKPD based on scientific inquiry in science class. Journal of Innovation in Educational and Cultural Research, 3(4), 731–736. https://doi.org/10.46843/jiecr.v3i4.242

Angelo, T. A. (1995). Beginning the dialogue: Thoughts on promoting critical thinking: Classroom assessment for critical thinking. Teaching of Psychology, 22(1), 6-7.

Anggraini, W., Saqila, M. S., Suryadi, A., & Suwarna, I. P. (2024). Peningkatan kemampuan berpikir kritis peserta didik pada materi energi terbarukan melalui PjBL-STEM dengan design thinking. Jurnal Pendidikan Matematika dan Sains, 13(2). https://jurnal.uny.ac.id/index.php/jpms/article/view/87690

Apriliyanti, H., Wardani, I. S., & Rusminati, S. H. (2025). Building students' critical thinking abilities through project based learning models on energy transformation material. Journal of Science Education Research, 9(1), 53–61. https://doi.org/10.21831/jser.v9i1.76149

Ariadila, S. N., Silalahi, Y. F. N., Fadiyah, F. H., Jamaludin, U., & Setiawan, S. (2023). Analisis pentingnya keterampilan berpikir kritis terhadap pembelajaran bagi siswa. Jurnal Ilmiah Wahana Pendidikan, 9(20), 664-669. https://doi.org/10.5281/zenodo.8436970

Aviyanti, L., Fratiwi, N. J., Gani, A. W., Salam, A., Simbolon, G. H. T., & Purwanto, M. G. (2025). Exploring HOTS on global warming concepts, self-efficacy and learning motivation among high school students. Momentum: Physics Education Journal, 9(2), 217-227. https://doi.org/10.24042/jipfalbiruni.v14i2.28194

Aviyanti, L., Fratiwi, N. J., Nurdini, N., Salam, A., & Nawas, A. (2025). Can multiple-choice items measure critical thinking in socio-scientific environmental issues? Evidence from a global warming assessment of grade 10 students using rasch analysis. Jurnal ilmiah pendidikan fisika Al-Biruni, 14(2), 33-53. https://doi.org/10.24042/jipfalbiruni.v14i2.28194

Cacik, S., & Widiyanti, I. S. R. (2024). Analysis of critical thinking ability of class X senior high school students. Journal of Research in Instructional. https://doi.org/10.30862/jri.v4i2.484

Dewi, A., Mukaromah, A., Ilham, M., & Arifin, Z. (2025). The effectiveness of project-based learning in improving students' critical thinking skills. Journal of Learning and Education, 10(4). https://doi.org/10.31004/jele.v10i4.1292

Ennis, R. H. (2011). The nature of critical thinking : an outline of critical thinking dispositions. 1–8.

Facione, P. A. (1990). Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction.

Gandi, A. S. K., Haryani, S., & Setiawan, D. (2021). The effect of project-based learning integrated STEM toward critical thinking skill. Journal of Primary Education, 10(1), 18–23. https://doi.org/10.15294/jpe.v10i1.33825

Halpern, D. F. (2014). Thought and knowledge: an introduction to critical thinking

Hartono, U., Amarullah, R. Q., & Mulyadi, E. (2022). Hakikat belajar menurut UNESCO serta relevansinya pada saat ini. Khidmatussifa, 1(2), 22–30. https://doi.org/10.56146/khidmatussifa.v1i2.65

Illahi, B. K., & Yurnetti, Y. (2023). Effect of the guided inquiry learning model assisted by scientific worksheet toward critical thinking skills. Physics Learning and Education, 1(1), 29–35. https://doi.org/10.24036/ple.v1i1.8

Isro, A. L., Anggraito, Y. U., & Bintari, S. H. (2021). Description of students' critical thinking skills in integrated PjBL-STEM learning on environmental change material. Journal of Innovative Science Education, 10(3), 237–243. http://journal.unnes.ac.id/sju/index.php/jise

Keller, J., & Suzuki, K. (2004). Learner motivation and E-learning design: A multinationally validated process. Journal of Educational Media, 29(3), 229–239. https://doi.org/10.1080/1358165042000283084

Maknuunah, L., Kuswandi, D., & Soepriyanto, Y. (2021). Project-Based Learning integrated with Design Thinking approach to improve students' critical thinking skill. Proceedings of ICITE 2021 (pp. 156–163). Atlantis Press. https://doi.org/10.2991/assehr.k.211210.025

Markula, A., & Aksela, M. (2022). The key characteristics of project-based learning: How teachers implement projects in K-12 science education. Disciplinary and Interdisciplinary Science Education Research, 4, Article 2. https://doi.org/10.1186/s43031-021-00042-x

Meirawati, K., Abdurrahman, A., & Jalmo, T. (2025). Improving critical thinking skills through the implementation of e-worksheets based on differentiated PjBL-STEM. Journal of Advanced Sciences and Mathematics Education, 5(2). https://doi.org/10.58524/jasme.v5i2.799

Octafianellis, D. F., Sudarmin, S., Wijayanti, N., & Panca, H. (2021). Analysis of student's critical thinking skills and creativity after problem-based learning with STEM integration. Journal of Science Education Research, 5(1), 31–37. https://doi.org/10.21831/jser.v5i1.41750

Organisation for Economic Co-operation and Development (OECD). (2023).

PISA 2022 results (Volume I): The state of learning and equity in education. OECD Publishing.

https://doi.org/10.1787/53f23881-en

Palangi, J., Jamhari, M., Agni, R., Laenggeng, A. H., Fardha, R., & Febriawan, A. (2025). Pengaruh Model Project Based Learning Berbasis STEM

Terhadap Keterampilan Berpikir Kreatif dan Motivasi Belajar Peserta Didik Pada Mata Pelajaran Biologi di SMAN 4 Palu. Bioscientist : Jurnal Ilmiah Biologi, 13(3), 1950–1960. https://doi.org/10.33394/bioscientist.v13i3.17434

Palennari, M., & Bahri, A. (2025). Implementasi pembelajaran berbasis proyek (project-based learning) berbasis strategi motivasi arcs pada materi perubahan lingkungan melalui kegiatan pengabdian dosen bersama mahasiswa di sman 11 pinrang. Barani: Journal of Community Service Learning, 1(1), 25–38. https://doi.org/10.58917/barani.v1i1.452

Putra, P. D. A., Sulaeman, N. F., Supeno, & Wahyuni, S. (2021). Exploring students' critical thinking skills using the engineering design process in a physics classroom. The Asia-Pacific Education Researcher, 32(1), 141–149. https://doi.org/10.1007/s40299-021-00640-3

Rachmawati, F. A., & Wiyatmo, Y. (2025). The effectiveness of a renewable energy e-worksheet in stem-project-based learning to improve students' critical thinking and collaboration skills. Jurnal Pendidikan Fisika 13(2), 119–132. https://doi.org/10.26618/jpf.v13i2.17432

Ramadhani, A. S., & Sulisworo, D. (2022). Peningkatan motivasi dan hasil belajar siswa pada pembelajaran fisika dengan model ARCS. Jurnal Genesis Indonesia, 1(02), 93–101. https://doi.org/10.56741/jgi.v1i02.94

Razzouk, R., & Shute, V. (2012). What is design thinking and why is it important? Review of educational research, 82(3), 330–348. https://doi.org/10.3102/0034654312457429

Rianto, P. A. M., Putra, P. D. A., & Ridlo, Z. R. (2023). Pengaruh model pembelajaran PjBL dengan pendekatan engineering design process pada pembelajaran IPA terhadap keterampilan berpikir kritis siswa SMP. Jurnal Pendidikan MIPA, 13(4). https://doi.org/10.37630/jpm.v13i4.1272

Safitri, W., Suyanto, S. ., & Prasetya, W. A. (2024). The influence of the stem-based engineering design process model on high school students' creative and critical thinking abilities. Jurnal Penelitian Pendidikan IPA, 10(2), 662–673. https://doi.org/10.29303/jppipa.v10i2.4765

Sarıkoç, Z., & Özerbaş, S. (2025). Evaluation of ARCS-based motivational design thinking (m-dt) education. International Journal of Research in Teacher Education, 16(3), 1–16. https://doi.org/10.29329/ijrte.2025.1355.01

Scriven, M., & Paul, R. (1987). Defining critical thinking: A draft statement for the National Council for Excellence in Critical Thinking Instruction. http://www.criticalthinking.org/pages/defining-critical-thinking/766

Sun, D., & Mohamad Ashari, Z. (2024). Project-based learning on promoting children's critical thinking skills: A systematic review. International Journal of Academic Research in Progressive Education and Development, 13(3), 807–820. https://doi.org/10.6007/IJARPED/v13-i3/21732

Tafakur, T., Retnawati, H., & Shukri, A. A. M. (2023). Effectiveness of project-based learning for enhancing students critical thinking skills: A meta-analysis. JINoP (Jurnal Inovasi Pembelajaran), 9(2), 191–209. https://doi.org/10.22219/jinop.v9i2.22142

Wahyuniyati, N. M., Suastika, I. N., & Mudana, I. W. (2025). Effectiveness of e-LKPD based on Liveworksheets on improving students' motivation and learning outcomes. Indonesian Journal of E-Learning and Multimedia, 4(2), 90–106. https://doi.org/10.58723/ijoem.v4i2.401

Widyastuti, A. (2022). Implementasi project based learning pada kurikulum 2022 prototipe merdeka belajar. PT Elex Media Komputindo

Wilson, K., & Defianty, M. (2024). The critical challenge for ELT in Indonesia: Overcoming barriers in fostering critical thinking in testing-oriented countries. TESOL in Context, 33(1). https://doi.org/10.21153/tesol2024vol33no1art2011

Zulkarnaen, Z., Rahayu, S., & Artayasa, I. P. (2025). Trends in project-based learning for developing critical thinking skills in science education: a bibliometric review. International Journal of Science Education and Science, 2(1), 26–34. https://doi.org/10.56566/ijses.v2i1.258