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Integration Of Pjbl-Stem And Virtual Laboratory: A Strategy To Improve Critical Thinking Skills Of Prospective Elementary School Teachers

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ABSTRACT

This study investigated the effectiveness of integrating Project-Based Learning in Science, Technology, Engineering, and Mathematics (PjBL-STEM) with a virtual laboratory in enhancing the critical thinking skills of prospective elementary school teachers in physics-oriented science learning. The study employed a pre-experimental one-group pretest–posttest design involving 112 students from the Madrasah Ibtidaiyah Teacher Education Study Program at Universitas Islam Negeri Alauddin Makassar. Participants were selected through total sampling across three classes. Data were collected using a 10-item essay-based critical thinking test covering interpretation, analysis, and conclusion-drawing skills. The instrument demonstrated satisfactory validity (Aiken's V ≥ 0.80) and reliability (Cronbach's α ≥ 0.70). Data were analyzed using descriptive statistics and Hake's normalized gain (N-Gain). The results showed substantial improvement in students' critical thinking skills. While all participants were initially categorized as poor, posttest results indicated that 25% achieved excellent, 70% good, 2% fair, and only 4% remained poor. The mean N-Gain was 0.75, indicating a high level of improvement. High gains were also observed across all indicators: interpretation (0.77), analysis (0.71), and conclusion drawing (0.76). These findings suggest that PjBL-STEM integrated with virtual laboratories effectively promotes critical thinking and supports the development of 21st-century competencies among prospective elementary teachers.

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1. INTRODUCTION

Critical thinking has become one of the most foundational competencies for navigating the complexity of contemporary life, work, and learning. Within the framework of 21st-century skills, it is widely characterized as the disciplined ability to analyze information, evaluate evidence, construct logical arguments, and arrive

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at warranted conclusions across diverse disciplinary and applied contexts (Bean & Melzer, 2021; Halpern & Dunn, 2021; Leś & Moroz, 2021). Far from being a content-neutral cognitive skill, critical thinking is increasingly framed as a core enabler for problem-solving, ethical reasoning, scientific literacy, and adaptive learning. Consequently, education systems worldwide are reconfiguring teaching and assessment practices to ensure that learners develop habits of mind compatible with rapidly evolving knowledge environments (Halpern & Dunn, 2021; Sutiani, 2021).

In the context of teacher education, and particularly in elementary teacher preparation programs such as the Madrasah Ibtidaiyah Teacher Education Study Program in Indonesia, the cultivation of critical thinking is doubly significant. Prospective elementary school teachers must not only acquire scientific and pedagogical content knowledge, but also be capable of translating that knowledge into instructional designs that nurture higher-order thinking among young learners. This dual demand makes the deliberate integration of pedagogical innovation and educational technology indispensable for shaping reflective, technologically literate, and intellectually agile teachers (Lintner, 2024; Seibert, 2021; Sutiani, 2021). Without such integration, science teacher education risks producing graduates who are knowledgeable about science yet underprepared to model the inquiry-driven dispositions that contemporary curricula require.

Among the most widely adopted pedagogical responses to this challenge is Project-Based Learning (PjBL) coupled with a Science, Technology, Engineering, and Mathematics (STEM) approach. The PjBL-STEM model centers learning around authentic, ill-structured projects that require learners to identify problems, design solutions, and evaluate outcomes through scientific inquiry (Salmah et al., 2025; Sukarma et al., 2024; Syam et al., 2024). By demanding active participation throughout the project cycle, PjBL-STEM cultivates metacognitive awareness, collaborative reasoning, and the analytical sophistication necessary for higher-order thinking, while embedding STEM content within meaningful real-world contexts (Purwaningsih et al., 2024; Rugh et al., 2021).

A growing empirical literature has linked PjBL-STEM to measurable improvements in critical thinking. Studies in physics, chemistry, and integrated science contexts report that the model creates productive opportunities for reflective and collaborative learning and strengthens scientific problem-solving by embedding design-thinking processes within instruction (Nur'aini et al., 2022; Saputra, 2021; Syam et al., 2024). These findings are consistent with broader evidence that contextualised, project-driven instruction promotes critical and creative thinking patterns and reinforces conceptual understanding through prolonged engagement with authentic tasks (Azzahra et al., 2025; Joronavalona et al., 2025; Santoso et al., 2021).

Despite this promise, the implementation of PjBL-STEM in higher education—particularly in resource-constrained institutions—faces persistent practical challenges. Among the most significant is restricted access to physical laboratory facilities, which limits opportunities for hands-on experimentation and impedes the very inquiry processes the model is designed to elicit (Li, 2025; Muchtar & Ding, 2024; Rahmadani et al., 2023; Salmah et al., 2025). Such constraints become particularly acute in large class sections, in programs that lack specialised science laboratories, and in distance- or hybrid-learning configurations that have proliferated since the COVID-19 pandemic. Under these conditions, the use of educational technology as a substitute or complement to physical experimentation has emerged as a strategic necessity rather than a luxury (Domenici, 2022; Imaduddin et al., 2021; Swandi et al., 2021).

Virtual laboratories represent one of the most consequential technology-based responses to this gap. They allow learners to perform scientific experiments through interactive simulations, free from the constraints of time, space, or the availability of physical apparatus (Azzahra et al., 2025; Najah & Indriyanti, 2024; Yurchenko, 2025). By visualizing abstract phenomena and enabling iterative manipulation of variables, virtual laboratories support conceptual understanding while encouraging learners to formulate hypotheses, collect data, test predictions, and redesign experiments. (Malik et al., 2025; W. Wahyudi et al., 2023). The pedagogical affordances of virtual laboratories thus closely parallel the cognitive demands of critical thinking itself.

Empirical evidence substantiates this alignment. Virtual laboratories have been shown to expand experimental learning opportunities, increase flexibility, and support deeper, more reflective engagement with scientific concepts (Laila & Anggaryani, 2021; Malik et al., 2025).Their integration is also congruent with the broader vision of 21st-century education, which emphasizes interactive, collaborative, and student-centered learning environments (Callaghan et al., 2021; Nikitina & Ishchenko, 2023). Where physical laboratories remain difficult to access, virtual laboratories provide a credible avenue for sustaining experiential learning at scale.

The conceptual case for combining PjBL-STEM with virtual laboratories is therefore compelling. Together, these approaches offer a robust pedagogical synergy in which authentic STEM projects are enacted within rich, manipulable digital simulation environments, allowing learners to interrogate complex experimental data and iterate on solution designs (Cortázar et al., 2021; Essien et al., 2024; Fadli et al., 2024). In this configuration, virtual laboratories function not merely as substitutes for missing equipment but as enabling infrastructure for exploratory and authentic problem-solving (Domenici, 2022; Rugh et al., 2021).

In the specific context of elementary school teacher education, the development of critical thinking skills constitutes a decisive determinant of successful science instruction. Prospective teachers must internalise scientific concepts at a sufficiently deep level to transpose them into developmentally appropriate classroom experiences anchored in project- and technology-based pedagogies (Wintribrata et al., 2025; Zulirfan & Yennita, 2022). Within Indonesian higher education, however, systematic empirical evidence on the effects of integrating PjBL-STEM and virtual laboratories specifically for prospective elementary teachers in physics-oriented science learning remains comparatively limited. Existing studies have explored the two approaches separately or in secondary-school settings, leaving open the question of how their joint implementation operates within pre-service elementary teacher cohorts.

Building on this gap, the present study empirically investigates how integrating PjBL-STEM with virtual laboratories influences the development of critical thinking skills among prospective elementary school teachers in a physics course. The study is guided by a single overarching research question: To what extent does integrating PjBL-STEM with virtual laboratory practice improve the critical thinking skills of prospective elementary school teachers, both overall and across the indicators of interpretation, analysis, and conclusion drawing.

2. METHOD

2.1. Research Design

The study employed a quantitative pre-experimental design, specifically a one-group pretest–posttest design. This design administers a pretest, an instructional treatment, and a posttest to a single intact group, enabling within-subject comparison of learning outcomes before and after the intervention. It was chosen because the research aim is to characterise the magnitude and patterning of change in students' critical thinking skills following the implementation of PjBL-STEM integrated with a virtual laboratory, rather than to compare its effect against an alternative intervention. The design structure is summarised in Table 1.

Table 1. One-group pretest–posttest research design.

Group	Pretest	Treatment	Posttest
Experiment	O_1	X	O_2

Note. O_1 = pretest of critical thinking skills; X = integrated PjBL-STEM learning treatment with virtual laboratory; O_2 = posttest of critical thinking skills.

Data were collected in three sequential stages. First, students completed a pretest of critical thinking skills before the implementation of the integrated PjBL-STEM and virtual laboratory intervention, providing a baseline of initial competence. Second, students participated in the instructional intervention, which combined STEM project-based learning activities with practical exercises conducted in a virtual laboratory environment. Third, after the entire instructional sequence was completed, students took a posttest using an instrument equivalent in difficulty and structure to the pretest to characterize their final critical thinking proficiency. The full procedural flow is presented in Figure 1.

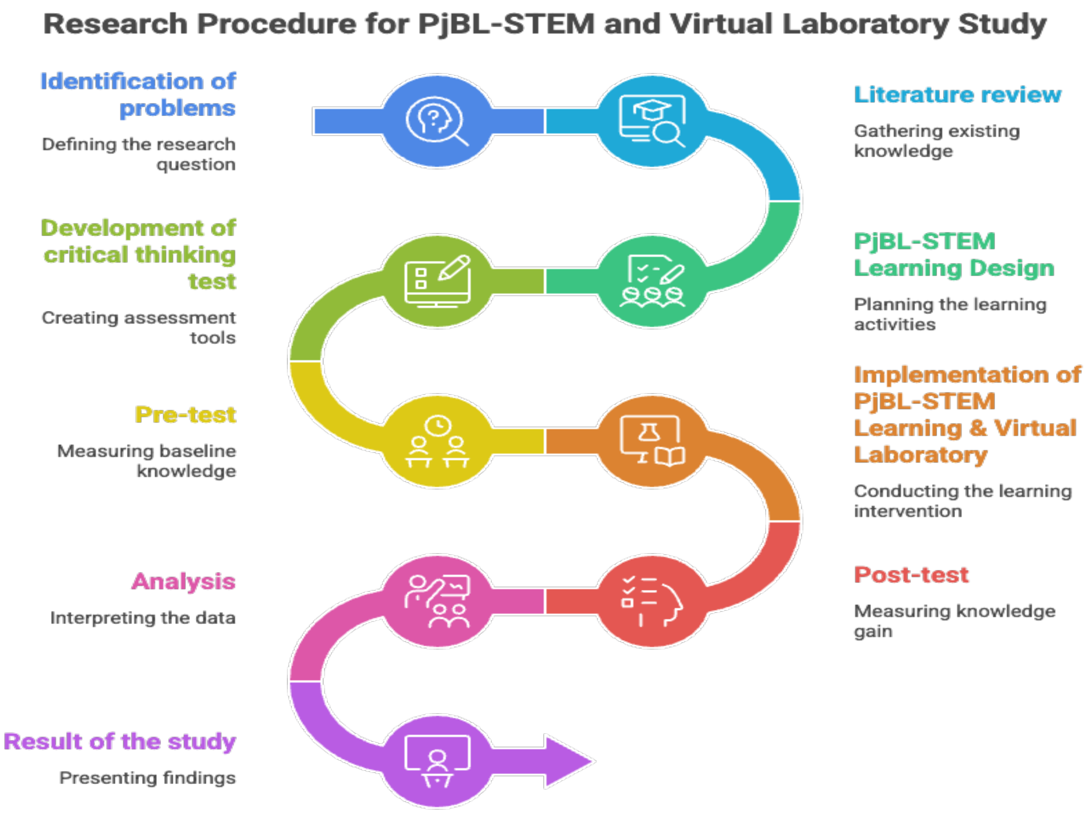

Figure 1.
Research flowchart of the integrated PjBL-STEM and virtual laboratory study.

2.2. Participants and Sampling

The study was conducted within the Madrasah Ibtidaiyah Teacher Education Study Program at Universitas Islam Negeri Alauddin Makassar during the 2025/2026 academic year. The research sample comprised 112 prospective elementary school teachers distributed across three intact classes, as detailed in Table 2. A total sampling technique was used, as the entire eligible population enrolled in the relevant physics-science course was included in the study; this approach maximises statistical power for a within-subjects design and removes selection bias associated with convenience sampling within a single program. All participants engaged in the same instructional intervention and assessment protocol.

Table 2. Distribution of research subjects across classes.

Class	Number of Students
A	38
B	37
C	37
Total	**112**

2.3. Learning Intervention: Integrated PjBL-STEM and Virtual Laboratory

The instructional intervention operationalized the integration of PjBL-STEM with virtual laboratory practice across a semester-long sequence of physics topics relevant to elementary science teaching, including energy, force, and electricity. The PjBL-STEM scaffolding followed a project lifecycle in which students engaged, in succession, in problem identification, scientific inquiry, design and prototyping, experimentation, analysis, and reflective evaluation of solutions, in line with established PjBL-STEM frameworks (Purwaningsih et al., 2024; Rugh et al., 2021; Sukarma et al., 2024). Within each project cycle, students worked collaboratively in small teams to formulate driving questions, develop conceptual and procedural plans, and produce tangible outputs.

Virtual laboratory activities were embedded as the primary experimentation environment within each project cycle. Students used interactive simulations to manipulate variables, generate data, and test predictions tied to their project tasks; this approach is consistent with the affordances of virtual laboratories documented in prior research (Fadli et al., 2024; Malik et al., 2025; Najah & Indriyanti, 2024; Pane et al., 2024). The simulation environment facilitated repeated experimentation, provided immediate feedback, and enabled the visualisation of variables that are typically inaccessible or challenging to manipulate in a physical apparatus. Consequently, it established cognitive conditions conducive to analysis, evaluation, and drawing conclusions (M. N. A. Wahyudi et al., 2024). Throughout the intervention, the lecturer facilitated meta-level reflection by prompting students to articulate their reasoning, justify methodological choices, and evaluate evidence in light of project objectives, drawing on the inquiry-supportive principles described by Sutiani (2021) and W. Wahyudi et al (2023)

2.4. Instrumentation

The principal research instrument was a critical thinking skills test consisting of essay-format questions designed to elicit reasoned written responses. The instrument was constructed using Facione's framework of critical thinking, with three core indicators retained for the present study: interpretation, analysis, and drawing conclusions (Khaeruddin & Bancong, 2022). The same instrument was administered for both the pretest and posttest, ensuring consistency of difficulty and construct coverage across the two measurement points. The operational definitions for each indicator are presented in Table 3.

Table 3. Critical thinking skills indicators adopted in the study.

No.	Indicator	Operational Definition
1	Interpretation	Students' ability to understand, interpret, and explain the meaning of information, data, or phenomena presented in scientific contexts.

2	Analysis	Students' ability to decompose information into key components, identify relationships among concepts, and evaluate the strength of arguments and evidence.
3	Conclusion	Students' ability to draw logical and accurate conclusions on the basis of data interpretation and analysis.

2.5. Validity and Reliability

The content validity of the instrument was established through expert judgment involving three specialists with complementary expertise: a subject-matter expert in physics, a learning-design expert, and an educational evaluation expert. Each item was independently rated, and the resulting scores were aggregated using Aiken's V index. All test items achieved a V value ≥ 0.80, which is conventionally interpreted as evidence of acceptable content validity. The use of Aiken's V as the basis for content validity has been widely applied in research on the development of critical thinking instruments (Khaeruddin & Bancong, 2022).

The reliability of the instrument was assessed using Cronbach's alpha in a preliminary trial conducted with students who were not part of the main research sample. The reliability coefficient obtained was $\alpha \geq 0.70$, indicating acceptable internal consistency for the quantitative measurement of critical thinking skills. The blueprint of the resulting instrument, including item distribution across indicators and representative cognitive activities, is presented in Table 4.

Table 4. Blueprint of the critical thinking skills test instrument.

Indicator	Question Form	Number of Items	Examples of Cognitive Activities
Interpretation	Essay	3	Explaining the relationships among physics concepts (e.g., energy, force, electricity) on the basis of phenomena or observational results.
Analysis	Essay	4	Analyzing cause-and-effect relationships among variables in scientific problems and evaluating supporting evidence.
Conclusion	Essay	3	Synthesizing principles of science from the data or cases presented to derive justified conclusions.
Total		**10 items**	

2.6. Data Analysis

Critical thinking scores were analyzed in three complementary ways. First, descriptive statistics (highest score, lowest score, and standard deviation) were computed for both the pretest and posttest to summarize the level and dispersion of student performance at each measurement point. Second, scores were classified into four ordinal categories of critical thinking proficiency, providing a qualitative characterization of student attainment, as detailed in Table 5. This categorization enables an interpretable view of the distribution of critical thinking abilities at the cohort level, both before and after the intervention.

Table 5. Categorization criteria for levels of critical thinking skills.

Level of Critical Thinking Skills	Student Score
Excellent	86 – 100
Good	70 – 85
Fair	55 – 69
Poor	< 55

Third, to evaluate the magnitude of improvement attributable to the intervention, normalized gain (N-Gain) analysis was conducted. N-Gain is a widely used measure in educational research because it accounts for the proportion of possible improvement actually achieved by each learner relative to their starting point, and is therefore robust to ceiling and floor effects (Firdaus & Wilujeng, 2018). N-Gain values were computed using the conventional Hake formula and classified according to the criteria summarized in Table 6.

Table 6. Categorization criteria of N-Gain scores.

Formula	Index ⟨g⟩	Criteria
$\langle g \rangle = (T_2 - T_1) / (I_s - T_1)$	$\langle g \rangle > 0.70$	High
T_1 = pretest score	$0.30 < \langle g \rangle \leq 0.70$	Medium
T_2 = posttest score	$\langle g \rangle \leq 0.30$	Low
I_s = ideal maximum score		

N-Gain analysis was performed at three levels: the cohort level (overall mean), per class (Classes A, B, and C), and per critical-thinking indicator (interpretation, analysis, and conclusion). This stratified approach was adopted in order to evaluate the effectiveness of the integrated PjBL-STEM and virtual laboratory intervention not only as a global outcome but also in terms of the dimension-specific patterning of cognitive growth.

3. RESULT AND DISCUSSION

3.1. Descriptive Statistics of Pretest and Posttest

The descriptive statistics for students' critical thinking scores indicate a clear pattern of improvement following the implementation of the integrated PjBL-STEM and virtual laboratory intervention. At the pretest stage, the highest score was 45, the lowest was 3, and the standard deviation was 7.87. These figures suggest that students' initial critical thinking abilities were relatively low, and that the score distribution was confined to a narrow band concentrated near the lower end of the scale. The fact that the highest pretest score did not approach the fair category's cut-off implies that, prior to the intervention, the majority of students were not yet able to apply critical thinking skills systematically across the test items. A side-by-side comparison of the pretest and posttest descriptive statistics is presented in Table 7.

Table 7. Comparative descriptive statistics for pretest and posttest scores in critical thinking skills.

Statistic	Pretest	Posttest
Highest score	45	100
Lowest score	3	28
Standard deviation	7.87	11.27

Following the intervention, the posttest results show a marked shift across all descriptive indices. The maximum score rose to 100, the minimum to 28, and the standard deviation increased to 11.27. The increase in the maximum score signals that the integrated PjBL-STEM and virtual laboratory environment was sufficiently rich to enable some students to attain ceiling-level performance, while the corresponding rise in the minimum score indicates that even students with the weakest baseline achieved tangible gains. The greater dispersion at posttest, evidenced by the larger standard deviation, suggests that learners' developmental trajectories diverged in line with their individual potentials—a pattern frequently reported in inquiry-rich, project-based environments where students take on differentiated roles within authentic tasks (Cortázar et al., 2021; Listiaji et al., 2022; Setiawan et al., 2025).

Taken together, the comparative analysis of pretest and posttest descriptive statistics signals that the implemented physics learning sequence was effective in elevating critical thinking skills across the cohort. The simultaneous rise in both the highest and the lowest scores, combined with the broader posttest distribution, indicates that the gains were not confined to a narrow subset of high-achieving students. Instead, they reflect a generalized improvement consistent with the documented effects of project-based and technology-supported instruction on higher-order thinking (Pane et al., 2024; Tuaputty et al., 2023; W. Wahyudi et al., 2023).

3.2. Categorical Distribution of Critical Thinking Skills

Examination of the percentage distribution of pretest scores across the four levels of critical thinking proficiency shows that 100% of students were classified in the poor category, while no students were classified in the fair, good, or excellent categories. This stark distribution corroborates the inference from the descriptive statistics: prior to the intervention, students collectively were unable to demonstrate the analytic, evaluative, and conclusion-drawing competencies required by the test items. The most plausible explanation is that students had limited prior exposure to higher-order thinking tasks in their preceding science courses, a pattern observed in other studies of pre-service teachers in Indonesian contexts (Listiaji et al., 2022; Septiadevana & Abdullah, 2024).

This baseline finding underscores the necessity of pedagogical strategies explicitly targeting higher-order thinking. Since all students initially fell within the poor category, the magnitude of improvement that could subsequently be observed depended substantially on the cognitive demands the intervention was able to mobilise. The pretest data thus provide a clear empirical justification for the design adopted: an instructional approach that systematically combines authentic project work with iterative experimentation in a virtual laboratory.

The posttest distribution diverges sharply from the pretest. Following the intervention, 70% of students were categorised as having good critical thinking skills, 25% as excellent, 2% as fair, and only 4% as poor. The convergence of the cohort toward the upper two categories indicates that the majority of students engaged systematically in interpretation, analysis, and conclusion-drawing when addressing the posttest items. The minority of students who remained in the lower categories suggests that some learners required additional or differentiated support, which is consistent with research showing that authentic, technology-mediated learning environments magnify—but do not eliminate—individual variability in cognitive growth (Hakim et al., 2020; Sujono et al., 2023). A direct comparison of pretest and posttest categorical distributions is presented in Table 8.

Table 8. Comparative percentage distribution of students' critical thinking skills categories before and after the intervention.le, 5 Baris, 3 Kolom

Category	Pretest (%)	Posttest (%)
Excellent	0	25
Good	0	70
Fair	0	2
Poor	100	4

The categorical shift illustrated in Table 8 is notably compelling. The migration of the cohort from a uniformly poor classification to a distribution primarily composed of good and excellent categories constitutes direct evidence that the integrated PjBL-STEM and virtual laboratory intervention significantly restructured learners' performance levels in a substantively meaningful manner. This finding aligns with previous reports indicating that PjBL-STEM enhances metacognitive engagement and analytical reasoning when implemented via scaffolded, project-based cycles. (Najah & Indriyanti, 2024; Salmah et al., 2025), and that virtual laboratory environments amplify these gains by enabling iterative, hypothesis-driven inquiry (Najah & Indriyanti, 2024; Yurchenko, 2025)

3.3. N-Gain Analysis: Overall Effectiveness of the Intervention

To quantify the magnitude of cognitive improvement, normalized gain (N-Gain) values were computed for each student. The cohort-level mean N-Gain reached 0.75, which falls within the high category according to the criteria specified in Table 6. At the individual level, 79 students were classified in the high N-Gain category, 32 in the medium category, and only 1 in the low category. The distributional pattern shown in Figure 2 indicates that the modal outcome of the intervention was a substantial—rather than marginal—improvement in critical thinking skills.

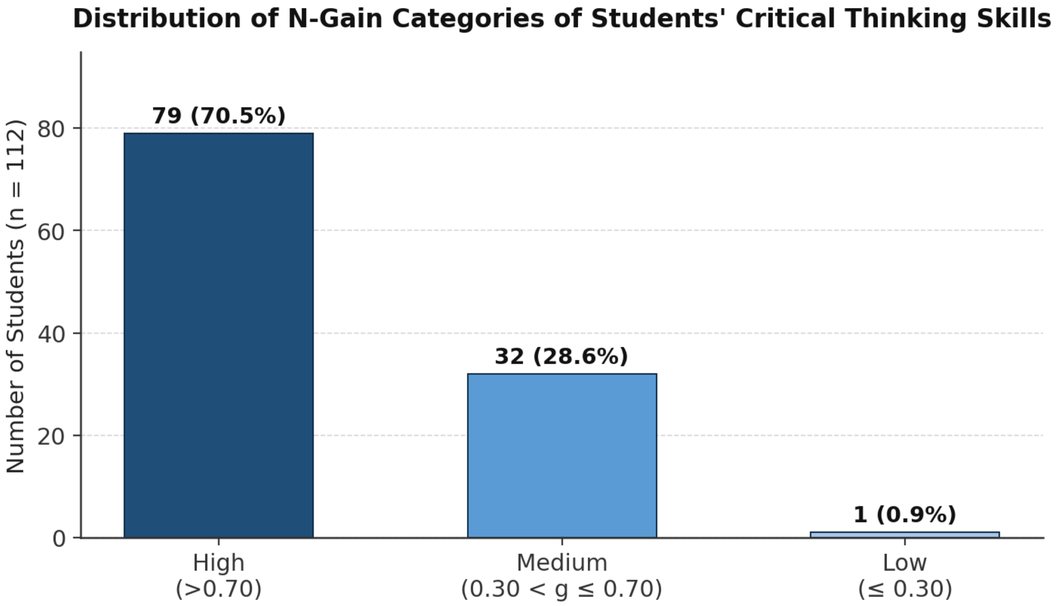

Figure 2. Distribution of N-Gain categories of students' critical thinking skills (n = 112).

Two patterns in Figure 2 merit emphasis. First, the dominance of the high N-Gain category (70.5% of students) indicates that the intervention reliably produced large within-subject improvements; the gain pattern is therefore not an artifact of a few exceptional learners. Second, the very small low-gain segment (less than 1%) suggests that virtually no student was unaffected by the intervention. Together, these patterns support the inference that the integrated learning approach functioned effectively across the cohort, in line with prior research showing that the joint implementation of project-based learning and virtual experimentation magnifies higher-order learning outcomes (Purwaningsih et al., 2024; Sujono et al., 2023; Trisnaningsih et al., 2021).

3.4. N-Gain by Critical Thinking Indicator

To examine whether the cognitive improvements were uniform across the dimensions of critical thinking, N-Gain values were computed separately for each indicator. The interpretation indicator achieved an N-Gain of 0.77, the conclusion indicator 0.76, and the analysis indicator 0.71. All three values fall within the high N-Gain category, and the overall mean N-Gain across indicators was 0.75. The indicator-level results, together with the high-gain threshold, are visualized in Figure 3.

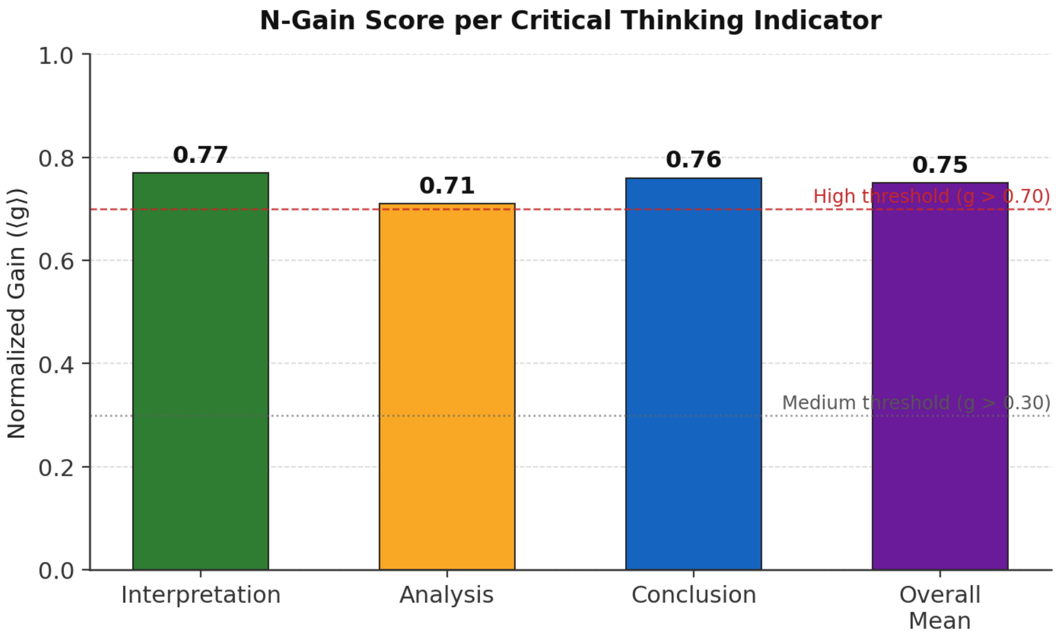

Figure 3. N-Gain scores per critical thinking indicator and overall mean.

The patterning of indicator-level gains is theoretically informative. The highest gain occurred for interpretation (⟨g⟩ = 0.77), suggesting that the combined affordances of authentic projects and interactive simulations were particularly effective at strengthening students' capacity to make sense of, identify patterns within, and explain scientific information. This is consistent with the proposition that virtual laboratories support interpretive reasoning by rendering abstract phenomena visible and manipulable (Malik et al., 2025; M. N. A. Wahyudi et al., 2024). The conclusion indicator likewise reached a high gain (⟨g⟩ = 0.76), indicating that students became substantially more capable of producing logically warranted closures grounded in data—an outcome that aligns with the role of PjBL-STEM in cultivating evidence-based reasoning during project synthesis (Nur'aini et al., 2022; Rahmawati et al., 2021).

The relatively lower (yet still high) gain for the analysis indicator (⟨g⟩ = 0.71) is itself instructive. Analysis requires decomposing complex information into structurally meaningful parts and evaluating relationships among them, a cognitive load typically heavier than interpretation or conclusion-drawing. The fact that the gain remains within the high category, while marginally trailing the other two indicators, is consistent with prior reports that analytic reasoning is the most cognitively demanding dimension of Facione-style critical thinking and tends to be the slowest to develop in technology-supported learning environments (Khaeruddin & Bancong, 2022; Listiaji et al., 2022). The result also parallels findings from research on virtual-laboratory-supported PjBL, in which interpretation and synthesis tend to outperform pure analysis in terms (Pane et al., 2024; Septiadevana & Abdullah, 2024).

3.5. Discussion

Considered as a whole, the results converge on a robust conclusion: the integration of PjBL-STEM with virtual laboratory practice produced substantial gains in the critical thinking skills of prospective elementary school teachers across all three Facione-aligned indicators. The shift in categorical distribution, the high overall N-Gain, and the uniformly high indicator-level gains mutually corroborate one another. Together, they extend prior findings showing that contemporary science education that emphasizes problem-solving, direct experiential learning, and educational technology effectively elevates higher-order thinking (Muzana et al., 2021; Setiawan et al., 2025; Sukarma et al., 2024).

The improvement pattern is also consistent with meta-analytic and review-based evidence indicating that project-based learning produces medium-to-high effect sizes on critical thinking and concurrently strengthens communication, collaboration, and problem-solving competencies (Purwaningsih et al., 2024; Sujono et al., 2023; Trisnaningsih et al., 2021). The growth observed here is the expected consequence of an instructional approach that requires students to analyze problems, evaluate information, and design solutions, since these are precisely the cognitive operations that problem- and project-based learning have been documented to elicit (Listiaji et al., 2022; Tuaputty et al., 2023; Wahdah et al., 2023).

Beyond the project-based component, the integration of virtual laboratory technology is plausibly central to the magnitude of the gains. By enabling students to manipulate variables, repeat experiments, and visualise otherwise inaccessible phenomena, virtual laboratories scaffold the very analytic and evaluative operations that the critical thinking test requires. Prior research has consistently linked virtual laboratory use to improved scientific reasoning, deeper conceptual engagement, and stronger higher-order thinking (Joronavalona et al., 2025; Najah & Indriyanti, 2024). Comparative evidence likewise indicates that integrating virtual laboratories with student-directed learning strategies surpasses traditional instructional formats in promoting critical thinking, engagement, and conceptual understanding, thereby positioning learning technology as a viable instrument for cultivating 21st-century competencies (Doyan et al., 2025; Hakim et al., 2020; Septiadevana & Abdullah, 2024).

Within the broader landscape of physics education, the present findings further support the proposition that innovative instructional materials and learning media exert a substantive influence on critical thinking. Recent reviews indicate that innovations in physics teaching materials demonstrate sizable effects on students' critical thinking abilities, positioning instructional innovation as a key lever for improving learning quality (Li, 2025; Rahmawati et al., 2021; W. Wahyudi et al., 2023). The current study contributes to this line of work by showing that the synergy of PjBL-STEM and virtual laboratory practice can be effectively transposed to a pre-service elementary teacher cohort, a population for which evidence in Indonesian higher education has been comparatively sparse.

The results bear several theoretical implications. First, they reinforce the conceptualization of critical thinking as an integrated competence whose components—interpretation, analysis, and conclusion—develop in coordinated fashion when learners are immersed in authentic, evidence-rich tasks (Bean & Melzer, 2021; Halpern & Dunn, 2021; Leś & Moroz, 2021). Second, they support the view that the productive integration of pedagogy and technology depends on alignment between cognitive demands and tool affordances; virtual laboratories that explicitly invite hypothesis testing and iterative design appear to be particularly conducive to higher-order thinking (Cortázar et al., 2021; Essien et al., 2024; Fadli et al., 2024). Third, they extend the case that PjBL-STEM functions not as a generic active-learning label but as a structured cognitive apprenticeship in scientific reasoning when its phases are coupled with appropriate digital infrastructures (Rugh et al., 2021; Sukarma et al., 2024; Syam et al., 2024).

3.6. Practical Implications

For pre-service elementary teacher education, the practical implications are direct. Programs constrained by limited physical laboratory access, large class sizes, or hybrid delivery formats can credibly deploy virtual laboratories within PjBL-STEM cycles to deliver substantive higher-order thinking outcomes (Domenici, 2022; Imaduddin et al., 2021; Swandi et al., 2021). The capacity of virtual laboratories to extend experimentation beyond the constraints of physical facilities makes them especially relevant for institutions that prepare large cohorts of elementary teachers and that need to ensure equitable access to inquiry-rich learning experiences (Wintribrata et al., 2025; Zulirfan & Yennita, 2022). Such integration also models the pedagogy that prospective teachers are expected to enact in their future classrooms, offering a coherent bridge between how they learn science and how they will eventually teach it (Lintner, 2024; Seibert, 2021; Sutiani, 2021).

Two caveats sharpen these implications. First, the persistence of a small minority of students in the fair and poor categories at posttest signals that not all learners benefit equally from a single instructional configuration. As prior literature notes, differentiated scaffolding, targeted practice with higher-order thinking items, or more intensive instructional support may be required to bring all students to higher proficiency levels (Hakim et al., 2020; Sujono et al., 2023). Second, the relatively lower gain for the analysis indicator suggests that explicit instruction in argument decomposition and evidence weighing should remain a focal element of PjBL-STEM cycles, even when the surrounding environment is otherwise rich in inquiry opportunities (Khaeruddin & Bancong, 2022; Rahmawati et al., 2021).

Several limitations should be acknowledged when interpreting the present findings. First, the use of a one-group pretest–posttest design precludes strong causal inference, as no control group was included for comparison; gains may therefore partially reflect maturation, retesting effects, or confounding instructional exposures, although the magnitude and patterning of the observed changes are difficult to attribute to such factors alone. Second, the study was conducted within a single program at a single institution, limiting the generalizability of the results to other teacher education contexts; replication across different programs and diverse learner populations would strengthen external validity. Third, the analysis focused on cognitive outcomes measured by an essay-based critical thinking test; affective and behavioural outcomes, such as motivation, self-efficacy, and collaborative dispositions, were not assessed and remain promising targets for future research. Finally, the intervention bundled PjBL-STEM with virtual laboratory practice as an integrated treatment; disentangling the unique contributions of each component will require dismantling designs that systematically vary the elements. These limitations notwithstanding, the magnitude and consistency of the observed gains, considered alongside the alignment with prior evidence, support the substantive value of the approach for pre-service elementary teacher education.

4. CONCLUSION

This study examined the effects of integrating PjBL-STEM with virtual laboratory practice on the critical thinking skills of 112 prospective elementary school teachers in a physics-oriented science course. The evidence is unambiguous: the intervention produced substantial gains across descriptive, categorical, and indicator-level analyses. Prior to the intervention, the entire cohort fell within the poor category of critical thinking proficiency. Following the intervention, the distribution shifted predominantly to the good (70%) and excellent (25%) categories, with only a small residual proportion in the fair (2%) and poor (4%) categories. The mean N-Gain of 0.75 falls within the high category, with most students classified as high in improvement. Indicator-level gains were uniformly high (interpretation = 0.77; analysis = 0.71; conclusion = 0.76), indicating that the intervention strengthened all three Facione-aligned dimensions of critical thinking, with interpretation and conclusion-drawing showing the greatest growth, and analysis still achieving a high gain despite its intrinsic cognitive complexity.

The findings substantiate the claim that integrating PjBL-STEM with virtual laboratories constitutes an effective pedagogical strategy for cultivating critical thinking in prospective elementary school teachers. Pre-service teacher education programs, particularly those operating under physical laboratory constraints, are encouraged to adopt this integrated model as an alternative instructional approach for advancing 21st-century cognitive competencies. Future research should employ controlled comparative designs to isolate the contributions of PjBL-STEM and virtual laboratory components, examine longer-term retention of critical thinking gains, and investigate transfer to teaching practices in elementary classrooms, including the affective and dispositional foundations that underpin sustained higher-order thinking.

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