

An Integrative PjBL-STEM and Virtual Laboratory Learning Model for Developing 21st Century Scientific Literacy in Junior High School Science

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Abstract: This study aims to analyze the effectiveness of integrating Project-Based Learning (PjBL) with Science, Technology, Engineering, and Mathematics (STEM) and virtual laboratories in enhancing 21st-century scientific literacy among junior high school students. A quasi-experimental design employing a one-group pretest-posttest model was used, involving 25 seventh-grade students from SMP Negeri 11 Yogyakarta. Data were collected using a scientific literacy test encompassing three dimensions: explaining phenomena scientifically, interpreting data and scientific evidence, and evaluating and using scientific information. The results revealed a significant difference between pretest and posttest scores ($p < 0.05$), with a normalized gain score of 0.62 categorized as medium. The greatest improvement occurred in the dimension of explaining phenomena scientifically (0.83), followed by interpreting data and scientific evidence (0.67), and evaluating and using scientific information (0.58). The integration of PjBL-STEM with virtual laboratories enhanced students' conceptual understanding and scientific reasoning, while providing initial support for the development of inquiry-related skills through interactive and contextual learning experiences. These findings indicate that the integrative PjBL-STEM model supported by virtual laboratory simulations is effective in promoting 21st-century scientific literacy and provides empirical evidence for science learning innovation in the context of Indonesian secondary education.

Keywords: 21st-Century Skills, PjBL-STEM, Scientific Literacy, Virtual Laboratory

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1. Introduction

The advancement of science and technology in the 21st century demands a transformation in education, particularly in science learning. Students are not only expected to master scientific concepts but also to develop critical thinking, creativity, collaboration, and communication skills collectively known as 21st-century skills (Haviz et al., 2018; Mulyani et al., 2023). In this context, scientific literacy becomes an essential competence that enables students to understand natural phenomena, apply scientific knowledge to solve problems, and make evidence-based decisions (Roy et al., 2025; Saputra et al., 2024).

However, various international assessments indicate that Indonesian students' scientific literacy remains relatively low. The 2018 Programme for International Student Assessment (PISA) results revealed that Indonesia's average science literacy score was below the OECD average (OECD, 2019). This suggests that science learning in schools has not yet fully fostered scientific thinking and the application of science in real-life contexts. Learning processes tend to emphasize rote memorization of concepts rather than inquiry, exploration, and contextual problem-solving experiences (Aswari et al., 2024; Ridani & Arianingrum, 2024).

One of the relevant approaches to fostering 21st-century scientific literacy is Project-Based Learning (PjBL). This model places students at the center of the learning process through project activities that require knowledge application, collaboration, and problem-solving (Hindun et al., 2024; Hudha et al., 2023; Rediani, 2024). The STEM (Science, Technology, Engineering, and Mathematics) approach complements this model by emphasizing interdisciplinary integration so that students can understand the connections between science and its real-world applications (Hudha et al., 2023; Le et al., 2023; Li et al., 2020). The integration of PjBL and STEM can enhance higher-order thinking skills, creativity, and scientific communication abilities (Siew & Ambo, 2018; Sun et al., 2022).

Nevertheless, the implementation of PjBL-STEM in schools often faces challenges such as limited laboratory facilities, practice materials, and instructional time (Pamungkas et al., 2025; Sarsale et al., 2024). Consequently, students have fewer opportunities to engage in hands-on experiments and scientific exploration. To address these limitations, the use of virtual laboratories has emerged as an effective alternative. Virtual laboratories enable students to conduct science experiments through interactive digital simulations that replicate real laboratory experiences (Gnesdilow, 2025; Jamah et al., 2022; Shambare & Simuja, 2022). Such media can enhance conceptual understanding, scientific process skills, and learning motivation (Al-nakhle, 2022; Fitriah & Zawanis, 2024; Natsir et al., 2025).

The integration of PjBL-STEM and virtual laboratories is expected to create innovative, contextual, and meaningful science learning. Through project-based problem-solving linked with digital experiments, students not only deepen their understanding of scientific concepts but also strengthen their critical thinking, problem-solving, and technological exploration skills. Consequently, this strategy has the potential to improve 21st-century scientific literacy, encompassing scientific knowledge, scientific competencies, and awareness of the role of science in everyday

life (Rahmadani et al., 2023; Utomo et al., 2025). However, empirical studies that specifically examine the integration of PjBL-STEM and virtual laboratories in the context of junior high school science learning in Indonesia remain limited. Therefore, this study aims to analyze the effectiveness of implementing a PjBL-STEM learning model assisted by virtual laboratories as an integrative pedagogical framework, rather than as a stand-alone instructional intervention, in enhancing students' 21st-century scientific literacy.

Based on this objective, the hypotheses of the study are formulated as follows:
 H1: There is a statistically significant difference between students' pretest and posttest scores in 21st-century scientific literacy after learning through the integrative PjBL-STEM and virtual laboratory model.

H2: The integrative PjBL-STEM and virtual laboratory learning model significantly improves each dimension of students' scientific literacy, including explaining scientific phenomena, interpreting data and scientific evidence, and investigating, evaluating, and using scientific information.

2. Method

This study employed a quasi-experimental design using a one-group pretest–posttest model to evaluate the effectiveness of integrating Project-Based Learning (PjBL) with STEM and virtual laboratories in enhancing students' 21st-century scientific literacy. This design enabled the researchers to measure changes in students' scientific literacy before and after the implementation of the learning intervention. The overall design of the study is presented in Table 1.

Table 1. One-Group Pretest–Posttest Research Design

| Group | Pretest | Treatment | Posttest |
|--------------|----------------|-----------|----------------|
| Experimental | O ₁ | X | O ₂ |

Notes:

O₁ = Pretest

X = PjBL-STEM learning with virtual laboratory

O₂ = Posttest

The study was conducted at SMP Negeri 11 Yogyakarta in the 2025/2026 academic year. The research sample consisted of 31 seventh-grade students selected purposively based on their readiness to participate in project- and technology-based learning. Prior to analysis, data completeness was verified. Six students who did not complete either the pretest or posttest were excluded using listwise deletion. Consequently, 25 complete and valid paired datasets were analyzed.

The research instrument consisted of a multiple-choice scientific literacy test validated by experts. The test was developed based on three dimensions of scientific literacy: scientific knowledge, scientific competence, and awareness of the role of science in daily life. Each indicator was measured within real-life contexts relevant to

the topics of Heat, Temperature, and Expansion. The same test was administered for both pretest and posttest, maintaining equivalent item difficulty and structure.

The learning process was implemented through the PjBL-STEM model integrated with virtual laboratory activities. The learning sequence included problem identification, project planning, exploration and experimentation through virtual simulations, and finally, product development and project presentation. Through these activities, students were expected to integrate conceptual understanding with scientific inquiry skills and connect science concepts with real-world phenomena.

Data from the pretest and posttest were analyzed both descriptively and inferentially. Descriptive statistics mean, standard deviation, minimum, and maximum were used to describe the distribution of students' scientific literacy scores. The improvement in scientific literacy was calculated using normalized gain (N-Gain), following Hake (1998), as shown in the following equation

$$g = \frac{S_{\text{post}} - S_{\text{pre}}}{100 - S_{\text{pre}}}$$

The obtained N-Gain values were then categorized into three levels of improvement, as shown in Table 2.

Table 2. N-Gain Interpretation Categories

| N-Gain Range | Category |
|----------------------|----------|
| $g < 0.30$ | Low |
| $0.30 \leq g < 0.70$ | Medium |
| $g \geq 0.70$ | High |

Normality of data distribution was tested using the Shapiro–Wilk test. Since the data were normally distributed ($p > 0.05$), a paired-sample t-test was employed to determine the significance of differences between pretest and posttest scores. The effect size was calculated using Cohen's d, interpreted as small ($d = 0.2$), medium ($d = 0.5$), or large ($d = 0.8$). All data analyses were performed using IBM SPSS Statistics 26.

This analytical approach was not only used to examine the effectiveness of PjBL-STEM integrated with virtual laboratories but also to map the improvement profiles of students' 21st-century scientific literacy across three key dimensions: scientific knowledge, scientific competence, and awareness of the role of science in everyday life.

3. Result and Discussion

Result

This study aimed to analyze the effectiveness of implementing STEM-based Project-Based Learning (PjBL) integrated with virtual laboratories in enhancing junior

high school students' 21st-century scientific literacy. The analysis was conducted using pretest and posttest data grouped into three dimensions of scientific literacy: (1) explaining phenomena scientifically, (2) interpreting data and scientific evidence, and (3) investigating, evaluating, and using scientific information. To obtain comprehensive results, the data analysis consisted of several stages, including normality testing, pretest-posttest comparison, normalized gain (N-Gain) analysis, and examination of learning outcomes for each literacy dimension.

Normality Test

Normality testing was performed using the Shapiro-Wilk test to determine whether the pretest and posttest data were normally distributed. The results are presented in Table 3.

Table 3. Shapiro-Wilk Normality Test Results

| Variable | Statistic | df | Sig. | Description |
|------------------------------|-----------|----|-------|-------------|
| Pretest Scientific Literacy | 0.914 | 25 | 0.038 | Not normal |
| Posttest Scientific Literacy | 0.973 | 25 | 0.723 | Normal |

Based on the results, the pretest data showed a significance value of 0.038 (< 0.05), indicating a non-normal distribution, while the posttest data were normally distributed ($p = 0.723 > 0.05$). Since one of the datasets did not meet the normality assumption, the Wilcoxon Signed Rank Test was used to analyze the differences between pretest and posttest scores.

Comparison of Pretest and Posttest Scores

The Wilcoxon test was employed to determine whether a significant difference existed between students' pretest and posttest scores after implementing the PjBL-STEM model assisted by virtual laboratories. The results are shown in Table 4.

Table 4. Wilcoxon Signed Rank Test Results

| Description | N | Mean Rank | Sum of Ranks |
|------------------------|--------|-----------|--------------|
| Negative Ranks | 0 | 0.00 | 0.00 |
| Positive Ranks | 25 | 13.00 | 325.00 |
| Ties | 0 | – | – |
| Z | -4.383 | | |
| Asymp. Sig. (2-tailed) | 0.000 | | |

The Wilcoxon test results indicate that all students experienced an increase in their posttest scores (positive ranks = 25, negative ranks = 0), with $Z = -4.383$ and $\text{Asymp. Sig. (2-tailed)} = 0.000 (< 0.05)$. These findings confirm a statistically significant difference between pretest and posttest scores. Moreover, the calculated effect size ($r = 0.88$; equivalent to Cohen's $d \approx 0.94$) indicates a large practical effect.

N-Gain Analysis of Scientific Literacy

Following the confirmation of a significant difference, normalized gain (N-Gain) was calculated to measure the magnitude of improvement in students' scientific literacy.

Table 5. Mean Scores and N-Gain of Scientific Literacy

| Variable | Mean Pretest | Mean Posttest | Mean N-Gain | Category |
|---------------------|--------------|---------------|-------------|----------|
| Scientific Literacy | 55.20 | 82.40 | 0.62 | Medium |

The mean N-Gain value of 0.62 falls within the medium category according Hake (1998) classification, indicating a substantial improvement in students' scientific literacy after the implementation of PjBL-STEM integrated with virtual laboratories.

Scientific Literacy Achievement by Dimension

To provide a more detailed description of student achievement, posttest results were analyzed according to the three dimensions of scientific literacy.

Table 6. Average Posttest Scores by Scientific Literacy Dimension

| Scientific Literacy Dimension | Mean Skor | Category |
|---|-------------|-------------|
| Explaining phenomena scientifically | 0.83 | High |
| Interpreting data and scientific evidence | 0.67 | Medium |
| Investigating, evaluating, and using scientific information | 0.58 | Medium |
| Overall scientific literacy | 0.70 | High |

As shown in Table 6, the overall mean scientific literacy score reached 0.70 (high category), indicating that the PjBL-STEM learning model assisted by virtual laboratories effectively enhanced students' 21st-century scientific literacy. The distribution of achievement across dimensions is illustrated in Figure 1.

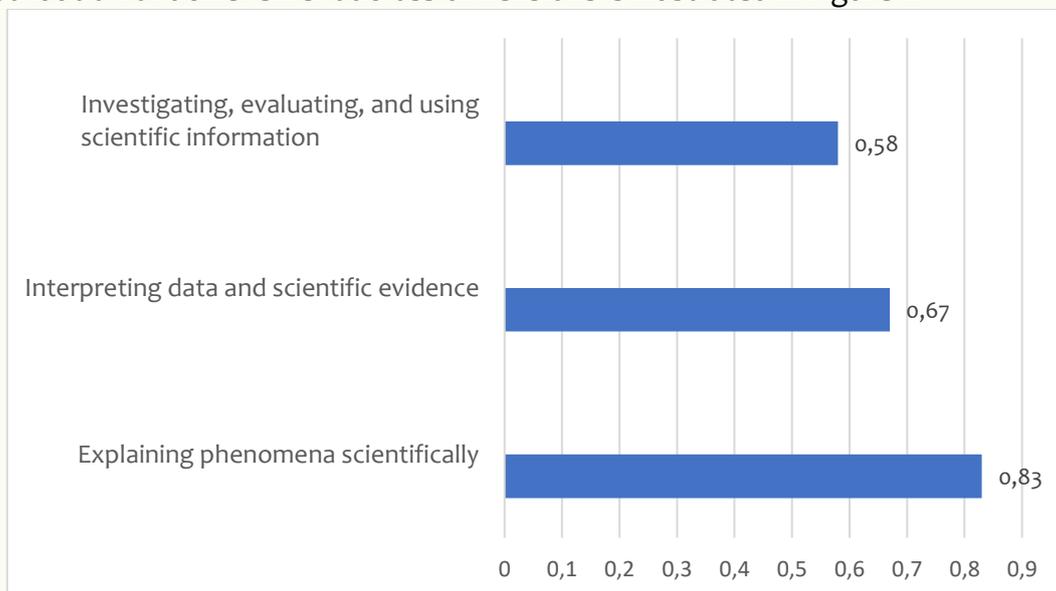


Figure 1. Histogram of Average Scores for Each Scientific Literacy Dimension

The results show that the highest achievement occurred in the dimension of explaining phenomena scientifically (0.83), followed by interpreting data and

scientific evidence (0.67), while the lowest achievement was observed in investigating, evaluating, and using scientific information (0.58).

Discussion

The present study demonstrates that the implementation of STEM-based Project-Based Learning (PjBL) integrated with virtual laboratories resulted in a significant improvement in junior high school students' scientific literacy, as reflected by the medium N-Gain value (0.62) and statistically significant Wilcoxon test results. Rather than merely confirming previous findings, this discussion critically situates the results within cross-contextual STEM education research, highlighting how differences in educational infrastructure, inquiry culture, and instructional scaffolding shape learning outcomes. Beyond confirming effectiveness, the following discussion critically examines how these findings compare with existing literature, how they relate to different educational contexts, and how they contribute to the broader STEM education research landscape.

The strongest improvement was observed in the dimension of explaining phenomena scientifically (0.83). This finding indicates that students were able to understand and apply scientific concepts to explain contextual phenomena such as heat transfer and material expansion. Collaborative and application-oriented project activities allowed students to actively construct knowledge through hands-on problem solving and contextualized tasks, consistent with constructivist learning principles (Blumenfeld et al., 2011). Similar outcomes have been reported in prior studies showing that PjBL enhances conceptual understanding and scientific reasoning by situating learning in meaningful, real-world contexts (Ardithayasa et al., 2022; Song et al., 2025).

However, compared with findings from studies conducted in well-resourced educational settings in Europe and East Asia, where PjBL-STEM has been shown to also yield high gains in inquiry and evaluative skills, the present results suggest a more uneven development of scientific literacy dimensions. In the Indonesian context, where students may have more limited prior exposure to inquiry-based learning and experimental autonomy, PjBL appears to more readily support conceptual explanation than advanced investigative reasoning. This contrast highlights the influence of contextual factors such as curriculum structure, assessment culture, and prior learning experiences on how STEM-based pedagogies translate into learning outcomes.

The dimension of interpreting data and scientific evidence achieved a medium mean score (0.67), indicating that students developed adequate abilities to read graphs, analyze tables, and draw conclusions from experimental data. Virtual laboratories played a crucial role in facilitating the visualization of abstract scientific processes and enabling students to explore variable relationships through interactive simulations. These findings align with previous research demonstrating that virtual simulations can effectively support data interpretation and evidence-based reasoning by reducing cognitive load and enhancing pattern recognition (Elmoazen et al., 2023; Lestari et al., 2023).

Nevertheless, some international studies have reported higher gains in data interpretation when virtual laboratories are embedded within explicitly scaffolded inquiry cycles rather than used as stand-alone tools (Chung et al., 2022; Kaldaras et al., 2024). In contrast, the moderate gains observed in this study suggest that while virtual laboratories were effective for visualization and exploration, additional instructional support may be required to fully optimize students' analytical engagement with data, particularly in junior high school settings.

From a cognitive and instructional design perspective, this pattern suggests that higher-order inquiry skills require more explicit and sustained scaffolding than conceptual explanation alone. The lowest performance was found in the dimension of investigating, evaluating, and using scientific information (0.58). This result indicates that students' inquiry-related and higher-order thinking skills remain less developed compared to their conceptual understanding. Students experienced difficulties in designing experiments, controlling variables, and critically evaluating research outcomes, a pattern that has also been documented in both Indonesian and international studies (Fitriah & Zawanis, 2024; Papalazarou et al., 2024; Trisnowati et al., 2021). Interestingly, some global studies report contradictory findings, suggesting that virtual laboratories alone can substantially enhance investigative skills when learners are given high levels of autonomy and iterative experimentation opportunities. The discrepancy with the present findings may stem from differences in instructional time, teacher guidance, and students' prior familiarity with inquiry-based learning. This suggests that virtual laboratories should not be viewed as a universal solution but rather as tools whose effectiveness depends on pedagogical integration and contextual readiness. Integrating virtual laboratories with hands-on experiments and explicit inquiry scaffolding may therefore be necessary to support deeper scientific investigation skills (Flegr et al., 2023; Miller et al., 2023; Tokatlidis et al., 2024).

Overall, these findings support the scientific literacy framework proposed by Bybee (2013) and OECD (2019), which emphasizes the integration of conceptual understanding, scientific competencies, and the application of science in everyday life. Within the broader STEM education research map, this study contributes empirical evidence from a developing-country context, highlighting both the potential and the limitations of PjBL-STEM supported by digital technologies in junior high school education. While much STEM education research originates from Western or technologically advanced educational systems, the present findings underscore the need to contextualize STEM pedagogies to local curriculum structures and learner characteristics.

Taken together, the implementation of PjBL-STEM integrated with virtual laboratories significantly enhanced students' scientific literacy and enriched their learning experiences in alignment with 21st-century educational demands. However, the uneven development across scientific literacy dimensions indicates that future implementations should move beyond effectiveness claims toward more refined instructional designs that explicitly target inquiry and evaluative competencies. Strengthening the alignment between virtual and real laboratory experiences,

alongside systematic inquiry scaffolding, may help bridge the gap between conceptual understanding and scientific investigation skills.

Limitations of the Study

Despite the promising findings, this study has several methodological limitations that should be acknowledged. First, the research employed a one-group pretest-posttest design without a control group. Therefore, the observed improvement in students' scientific literacy cannot be attributed solely to the integrative PjBL-STEM and virtual laboratory learning model. Second, the sample size was relatively small ($n = 25$) and drawn from a single junior high school, which may limit the generalizability of the findings. Third, the study is subject to potential maturation bias and testing effects, as students' performance may have improved due to natural developmental processes or increased familiarity with the test instruments. Future research is recommended to employ experimental or quasi-experimental designs with control groups, larger and more diverse samples, and repeated measurements to strengthen causal inference.

Implications for Educational Policy and Junior High School Science Curriculum

The findings of this study suggest important implications for educational policy, particularly in supporting the integration of STEM-oriented Project-Based Learning and digital learning technologies in junior high school science education. The observed improvement in students' 21st-century scientific literacy indicates that policy frameworks should facilitate adequate digital infrastructure, teacher professional development, and curriculum flexibility to enable the effective implementation of project-based and technology-enhanced learning models. Policies that promote the use of virtual laboratories may help schools address limitations in physical laboratory facilities while maintaining inquiry-based and experiential science learning.

From a curriculum development perspective, the results highlight the relevance of embedding PjBL-STEM approaches within the junior high school science curriculum to foster scientific literacy across cognitive, procedural, and contextual dimensions. While project-based learning aligned with real-life contexts effectively supported students' conceptual understanding, the relatively lower performance in investigative and evaluative skills indicates a need for more structured opportunities for scientific inquiry and data evaluation. Integrating virtual laboratories with hands-on experiments, accompanied by explicit inquiry scaffolding, may strengthen these competencies and better align the science curriculum with 21st-century learning demands.

4. Conclusion

This study concludes that integrating Project-Based Learning (PjBL) and STEM supported by virtual laboratories enhances students' 21st-century scientific literacy by strengthening conceptual understanding, data interpretation, and the application of scientific knowledge through contextual and interactive learning experiences.

From a theoretical perspective, the findings support constructivist and scientific literacy frameworks by demonstrating that integrated PjBL-STEM learning more strongly promotes explanatory and conceptual dimensions of literacy than investigative competencies, indicating that scientific inquiry skills require explicit scaffolding and sustained engagement with scientific practices. From an instructional standpoint, the results suggest that PjBL-STEM assisted by virtual laboratories can serve as an effective approach for junior high school science learning, particularly in contexts with limited laboratory resources; however, to foster balanced literacy development, STEM-based instruction should intentionally integrate guided inquiry, structured experimental design, and alignment between virtual and hands-on laboratory activities to strengthen students' investigative and evaluative skills.

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