



The Role of Virtual Laboratories in Project-Based Learning to Improve Students' Critical Thinking Skills in Biology Education

Muhammad Fuad^{1*}, Risqah Amaliah Kasman², Rahmania Rahman³, Armin Arif⁴, Herwandi⁵

^{1,2,5}Institut Teknologi dan Kesehatan Permata Ilmu Maros, Maros, Indonesia

³Universitas Negeri Manado, Manado, Indonesia

⁴Universitas Megarezky, Makassar, Indonesia

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ABSTRACT

Purpose: This study aimed to examine changes in students' critical thinking skills following the implementation of Project-Based Learning (PjBL) integrated with a virtual laboratory in biology learning, particularly on cell structure and function. **Methods:** A quantitative approach with a quasi-experimental pretest–posttest control group design was employed at SMA Pergis Maros, Indonesia. The participants were 50 Grade X students, comprising 26 students in the experimental group and 24 in the control group. The experimental group received PjBL integrated with a virtual laboratory, while the control group received conventional instruction. Data were analyzed descriptively using pretest and posttest mean scores and normalized gain (N-Gain). **Findings:** The experimental group's mean score increased from 62.69 to 64.42, representing a gain of 1.73 points, while the control group's mean score increased from 42.29 to 59.79, representing a gain of 17.50 points. The N-Gain values calculated from group means were 0.046 for the experimental group and 0.303 for the control group. Descriptively, the control group demonstrated greater improvement. However, the absence of individual-level data prevented inferential statistical testing. **Research Implications:** The findings highlight the importance of evaluating instructional implementation, assessment alignment, and students' initial abilities when integrating virtual laboratories into biology learning. **Originality:** This study provides context-specific descriptive evidence concerning virtual-laboratory-integrated PjBL for teaching cell structure and function in senior high school biology.



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INTRODUCTION

Biology learning at the senior high school level requires students not only to master concepts and recall facts but also to develop critical thinking skills to understand biological phenomena, analyze information, evaluate evidence, and draw conclusions based on observations. Critical thinking is essential because biology is closely related to scientific processes that require students to connect theoretical concepts with empirical evidence. Students need learning experiences that encourage them to ask questions, identify problems, formulate hypotheses, and explain biological phenomena logically. However, developing these skills requires learning approaches that go beyond information delivery and provide opportunities for students to participate actively in investigation and problem-solving activities. In this context, selecting an instructional model that integrates scientific activities, conceptual exploration, and product development is an important aspect of improving the quality of biology education.

One biology topic that requires instructional approaches supporting visualization and investigation is cell structure and function. This topic covers cell organization, organelle characteristics, and the relationships between the structures and functions of cellular components in sustaining life. Understanding these concepts can be challenging because most cellular structures are microscopic and cannot be observed directly without appropriate instruments. Riyadi and Saptano (2025) explained that learning about cell structure and function requires visualization support to help students understand cellular structures and organelles while encouraging logical reasoning and independent learning. Difficulties in visualizing microscopic biological structures may also limit students' ability to establish

conceptual connections between the form, structure, and function of organelles. Therefore, instruction on cell structure and function should be designed to help students not only identify organelles and describe their characteristics but also analyze functional relationships among cellular components, predict the consequences of structural changes, and provide scientific explanations based on available evidence.

One approach that may address these learning needs is the use of virtual laboratories. A virtual laboratory is a digital learning environment that allows students to conduct simulations, observe representations of scientific objects or processes, manipulate selected variables, and analyze investigation results without relying entirely on physical laboratory facilities. In biology education, this technology is relevant for studying objects and processes that are difficult to observe directly, including cell structures and molecular-level processes. [Byukusenge et al. \(2022\)](#), in their literature review of virtual laboratory use in biology education, found that virtual laboratories have the potential to support conceptual understanding, practical skills, and student motivation. Meanwhile, [Meronda et al. \(2025\)](#) identified the potential of virtual laboratories to strengthen conceptual understanding, scientific literacy, analytical abilities, and several cognitive skills in science education. These findings suggest that virtual laboratories can provide an exploratory learning environment that supports active learning. Nevertheless, their benefits cannot be assumed to emerge automatically from technology use alone. They require instructional designs that guide students to interpret simulation results, evaluate information, and construct conclusions based on evidence.

The development of critical thinking skills also requires an instructional model that allows students to investigate problems, make decisions, and justify their reasoning. Project-Based Learning (PjBL) is an instructional model that places projects at the center of the learning process, from formulating driving questions and planning activities to conducting investigations, developing products, and evaluating outcomes. Through these stages, students have opportunities to identify problems, collect and process information, test hypotheses, collaborate, and communicate arguments based on their findings. Research by [Suwistika et al. \(2024\)](#) indicates that the Problem-Oriented Project-Based Learning model has the potential to develop critical and creative thinking skills among secondary school students. In addition, research on problem-based learning and the development of critical thinking in biology education emphasizes the importance of instructional models that encourage active student engagement in reasoning processes. Thus, PjBL is pedagogically relevant to teaching cell structure and function because students can be guided to produce investigation-based outputs, such as interactive cell models, visual media illustrating relationships between organelle structures and functions, or analytical reports on cellular phenomena.

Integrating virtual laboratories into PjBL may strengthen the connection between digital exploration and project-based problem-solving. Virtual laboratories can serve as investigative tools for observing cell structures, comparing organelle characteristics, exploring structure–function relationships, and collecting information needed to develop project outputs. Students can subsequently analyze and discuss the results of their exploration to construct scientific explanations, evaluate the accuracy of information, and justify conclusions based on evidence. In this way, virtual laboratories function not merely as visualization media but as an integral component of the investigative process within PjBL. Theoretically, this integration may create a learning environment that connects representations of abstract concepts with activities involving analysis, evaluation, inference, and explanation. However, the effectiveness of this integration needs to be established empirically, particularly to determine whether using virtual laboratories contributes additional benefits to students' critical thinking skills compared with implementing PjBL without virtual laboratories.

Previous studies have examined the benefits of virtual laboratories and the application of project-based learning in developing students' thinking skills. For example, [Rahmasari and Raharjo \(2023\)](#) reported differences in senior high school students' critical thinking skills following the use of interactive virtual laboratories in learning about the circulatory system. Meanwhile, research on PjBL has demonstrated the potential of this instructional model to support critical thinking development through investigative activities and project completion. Nevertheless, findings from studies involving different biological topics or instructional models cannot be directly generalized to cell structure and function or to different combinations of instructional interventions. Based on the literature considered, further investigation is needed to specifically compare virtual-laboratory-integrated PjBL with PjBL without virtual laboratories in teaching cell structure and function. Such a comparison is important for distinguishing the general contribution of PjBL from the additional contribution of virtual laboratories in supporting students' critical thinking processes.

Based on this rationale, the present study aims to analyze the role of integrating virtual laboratories into Project-Based Learning in developing senior high school students' critical thinking skills in the topic of cell structure and function. Specifically, this study compares the critical thinking skills of students participating in virtual-laboratory-integrated PjBL with those of students participating in PjBL without virtual laboratories. It also examines changes in critical thinking indicators following the instructional intervention. The findings are expected to provide empirical evidence regarding the added value of virtual laboratories in project-based biology learning and inform teachers in

designing biology instruction that promotes scientific investigation, evidence-based reasoning, and conceptual understanding of cell structure and function.

METHOD

Research Design

This study employed a quantitative approach using a quasi-experimental method with a pretest–posttest control group design. The study aimed to examine changes in students' critical thinking skills following the implementation of Project-Based Learning (PjBL) integrated with a virtual laboratory in biology learning, specifically on the topic of cell structure and function. The experimental group received instruction using PjBL integrated with a virtual laboratory, whereas the control group received conventional instruction. Both groups completed a pretest before the instructional intervention and a posttest after the intervention to assess changes in their critical thinking scores. The research design is presented in Table 1.

Table 1. Pretest–Posttest Control Group Design

Group	Pretest	Treatment	Posttest
Experimental	O ₁	X ₁	O ₂
Control	O ₁	X ₂	O ₂

Note: O₁ represents the initial measurement conducted before the instructional intervention; O₂ represents the final measurement conducted after the intervention; X₁ represents Project-Based Learning integrated with a virtual laboratory; and X₂ represents conventional instruction.

Population and Sample

The study was conducted at SMA Pergis Maros, located at Jl. Dr. Ratulangi No. 62, Turikale Village, Turikale District, Maros Regency, South Sulawesi, Indonesia. The study population consisted of all Grade X students enrolled in the first semester of the 2025/2026 academic year, comprising four classes. The sample was selected using cluster random sampling, with intact classes serving as the sampling units. Class X-2 was designated as the experimental group, consisting of 26 students, while Class X-3 was designated as the control group, consisting of 24 students. The total sample comprised 50 students. The experimental group received PjBL integrated with a virtual laboratory, while the control group received conventional instruction on cell structure and function.

Research Instrument and Data Collection

Students' critical thinking skills were assessed using pretest and posttest scores. The pretest was administered before the instructional intervention to establish the initial performance of both groups, while the posttest was administered after the intervention to assess their subsequent performance. The scores were used to describe changes in critical thinking skills in the experimental and control groups.

The available dataset consisted of group mean scores rather than individual student scores. The experimental group obtained a mean pretest score of 62.69 and a mean posttest score of 64.42. The control group obtained a mean pretest score of 42.29 and a mean posttest score of 59.79. The maximum possible score was 100. Details concerning the number of test items, the specific critical thinking indicators, the scoring rubric, and the validity and reliability of the instrument should be reported based on the actual assessment procedures used in the study.

Data Analysis

The data were analyzed descriptively to examine changes in students' critical thinking scores between the pretest and posttest. The mean score difference was calculated by subtracting the pretest mean from the posttest mean for each group. Based on the available group means, the experimental group obtained an N-Gain of 0.046, while the control group obtained an N-Gain of 0.303. These values were interpreted descriptively using commonly applied N-Gain categories. Because individual student scores and measures of variability were unavailable, inferential statistical tests, including ANCOVA, could not be conducted. Consequently, the findings were interpreted in terms of descriptive differences rather than statistical significance or definitive causal effects.

RESULTS

Changes in Students' Critical Thinking Scores

The analysis examined changes in students' critical thinking scores following biology instruction on cell structure and function. The experimental group consisted of 26 students who participated in Project-Based Learning (PjBL) integrated with a virtual laboratory, while the control group consisted of 24 students who received conventional instruction. The analysis was based on the available group mean scores from the pretest and posttest.

Table 2. Mean Pretest and Posttest Scores of Students' Critical Thinking Skills

Group	N	Pretest	Posttest	Score Change
Experimental	26	62.69	64.42	+1.73
Control	24	42.29	59.79	+17.50

As presented in Table 2, the experimental group obtained a mean pretest score of 62.69 and a mean posttest score of 64.42, indicating an increase of 1.73 points. The control group obtained a mean pretest score of 42.29 and a mean posttest score of 59.79, indicating an increase of 17.50 points. Thus, the observed increase in the control group was 15.77 points greater than that in the experimental group. The two groups also differed in their initial performance. Before the intervention, the experimental group's mean score was 20.40 points higher than that of the control group. This initial difference is important when interpreting the posttest results because the groups did not begin with the same mean level of critical thinking performance.

Normalized Gain Analysis

Normalized gain (N-Gain) was calculated from the group mean scores using a maximum possible score of 100. The calculation was intended to describe the relative change in scores in relation to the improvement that was still possible.

Table 3. Normalized Gain Based on Group Mean Scores

Group	Pretest	Posttest	N-Gain	Category
Experimental	62.69	64.42	0.046	Low
Control	42.29	59.79	0.303	Moderate

The experimental group obtained an N-Gain of 0.046, which falls within the low category, while the control group obtained an N-Gain of 0.303, which falls within the moderate category under the commonly used classification in which values below 0.30 are low, values from 0.30 to below 0.70 are moderate, and values of 0.70 or higher are high.

These results indicate that, descriptively, the control group demonstrated a greater normalized increase than the experimental group. However, the values were calculated from group means rather than individual student scores. Therefore, they represent group-level descriptive estimates and should not be interpreted as the mean of individual N-Gain scores.

The available data do not include individual scores or measures of variability. Consequently, statistical significance, confidence intervals, and inferential effect sizes could not be established. The observed differences should therefore be interpreted as descriptive findings rather than evidence of a statistically significant difference between the instructional approaches.

DISCUSSION

Interpretation of Changes in Critical Thinking Scores

The findings indicate that both groups experienced an increase in mean critical thinking scores following instruction on cell structure and function. However, the magnitude of the observed increase differed between the groups. The experimental group, which participated in PjBL integrated with a virtual laboratory, showed an increase of 1.73 points, whereas the control group showed an increase of 17.50 points. This descriptive pattern does not demonstrate the expected advantage of the integrated intervention. Instead, it highlights the importance of examining students' initial abilities, instructional implementation, and the characteristics of the learning activities when evaluating technology-supported project-based learning.

One important consideration is the difference in the groups' initial mean scores. The experimental group started with a mean pretest score of 62.69, compared with 42.29 in the control group. This difference of 20.40 points suggests that the groups had different starting levels of critical thinking performance. Students in the experimental group also had less room for improvement before reaching the maximum possible score of 100. Nevertheless, the higher initial score alone does not establish why the experimental group demonstrated a smaller increase. Other factors, including the implementation of the instructional model, students' engagement, task difficulty, and the alignment between learning activities and assessment items, may also have contributed. These possibilities require additional evidence and cannot be confirmed from the available group means.

The Potential Contribution of Virtual Laboratories to Project-Based Learning

The integration of virtual laboratories into PjBL has a plausible pedagogical rationale for teaching cell structure and function. Cellular structures are microscopic, and students may find it difficult to understand the relationships between organelle structures and their biological functions through static illustrations or verbal explanations alone. Virtual laboratories may provide interactive visual representations that enable students to explore cellular components,

compare structures, and examine relationships among biological processes (Laubscher et al., 2024; Navarro et al., 2024).

Within PjBL, these exploratory activities can be connected to the development of a project. Students may investigate a biological question, gather information through virtual exploration, evaluate evidence, and use their findings to develop an explanatory model or other scientific product. Such activities may create opportunities to practice critical thinking through interpretation, analysis, inference, evaluation, and evidence-based explanation (Fuad et al, 2026).

However, the potential benefits of virtual laboratories depend on how they are integrated into the learning process. Merely providing access to a simulation does not guarantee that students will engage in higher-order reasoning. The instructional design must require students to formulate questions, explain observations, compare alternative interpretations, and justify their conclusions. Similarly, PjBL must involve meaningful investigation and decision-making rather than simply completing a project product. These considerations provide a theoretical explanation for why the integration may be valuable, but the present descriptive data do not establish whether these mechanisms occurred or explain the relatively small score increase in the experimental group (.Ayer Miller et al., 2025).

Implications for Biology Teaching

The findings provide a reason to examine the implementation of PjBL integrated with virtual laboratories more closely. Teachers may need to ensure that virtual laboratory activities are explicitly connected to the driving question and the final project. For example, students could investigate how differences in organelle structure relate to cellular functions and then develop an evidence-based model explaining these relationships. During the project, teachers could ask students to justify their interpretations, evaluate the reliability of their evidence, and explain how their conclusions follow from their observations (Madrasah & Bancong, 2026).

Assessment should also align with the intended development of critical thinking. Tests should include questions that require students to interpret biological information, analyze relationships, evaluate explanations, draw conclusions, and propose solutions rather than simply recall the names and functions of organelles. Such alignment would help determine whether the instructional intervention supports the specific reasoning skills targeted by the study. For future implementation, teachers and researchers should also document instructional fidelity, student participation, completion of project stages, and actual use of the virtual laboratory. These data would help clarify whether the planned instructional approach was implemented as intended and identify areas requiring improvement.

Limitations of the Study

Several limitations must be considered when interpreting these findings. First, the available dataset contains only group mean pretest and posttest scores. Individual student scores, standard deviations, and score distributions were not available. Therefore, inferential analyses such as ANCOVA could not be conducted, and it was not possible to determine whether the observed differences were statistically significant.

Second, the initial mean scores differed substantially between the experimental and control groups. This imbalance complicates the interpretation of changes and limits conclusions about the relative contribution of the instructional interventions. Third, the available data do not include information about the specific critical thinking indicators assessed, the validity and reliability of the instrument, or the implementation of the PjBL intervention. Consequently, the findings cannot identify which critical thinking skills changed or explain the mechanisms underlying the observed score patterns (Al-Buraiki et al., 2025). Further analysis using individual student data, together with documentation of the instructional process and instrument quality, would provide a stronger basis for evaluating the relationship between virtual-laboratory-integrated PjBL and critical thinking skills.

CONCLUSION

This study examined changes in students' critical thinking skills following biology instruction on cell structure and function through Project-Based Learning (PjBL) integrated with a virtual laboratory. The descriptive findings indicated that the experimental group's mean score increased from 62.69 in the pretest to 64.42 in the posttest, representing an increase of 1.73 points. Meanwhile, the control group's mean score increased from 42.29 to 59.79, representing an increase of 17.50 points. The normalized gain calculated from the group mean scores was 0.046 for the experimental group and 0.303 for the control group. These findings indicate that the observed improvement was greater in the control group than in the experimental group. However, because the groups differed in their initial mean scores and individual-level data were unavailable, the findings do not establish whether the differences between the instructional approaches were statistically significant. Therefore, no definitive conclusion can be drawn regarding the superiority of PjBL integrated with a virtual laboratory over conventional instruction. Further research should incorporate individual student data, appropriate inferential statistical analyses, and systematic evaluation of instructional implementation to

provide stronger evidence regarding the contribution of virtual laboratories to the development of critical thinking skills in biology learning.

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AUTHOR CONTRIBUTION STATEMENT

MF contributed to conceptualization, research methodology, data collection, and manuscript preparation. RAK contributed to the development of the research design, validation of the research instruments, data analysis, and

manuscript revision. RR contributed to data collection, literature review, and manuscript editing. AA contributed to methodological review, interpretation of findings, and critical revision of the manuscript. H contributed to supervision, validation of the research process, and final manuscript review. All authors reviewed and approved the final version of the manuscript.

AI DISCLOSURE STATEMENT

The authors used ChatGPT (OpenAI) during the preparation of this manuscript to assist with academic writing, language refinement, manuscript structuring, and the organization of research methods and results. After using this tool, the authors reviewed and edited the generated content as necessary and take full responsibility for the accuracy, integrity, and final content of the publication.

***Muhammad Fuad (Corresponding Author)**

Program Studi Pengelolaan Sumberdaya Perairan,
Institut Teknologi dan Kesehatan Permata Ilmu Maros,
Jl. Pallantikan Buttatoa, Kabupaten Maros, Sulawesi Selatan 90516, Indonesia
Email: muhammadfuad@itkpi.ac.id

Risqah Amaliah Kasman

Program Studi Sosial Ekonomi Perikanan,
Institut Teknologi dan Kesehatan Permata Ilmu Maros,
Jl. Pallantikan Buttatoa, Kabupaten Maros, Sulawesi Selatan 90516, Indonesia
Email: risqahamaliahkasman@itkpi.ac.id

Rahmania Rahman

Program Studi Pendidikan Ilmu Pengetahuan Sosial (IPS),
Universitas Negeri Manado,
Jl. Kampus Unima, Kelurahan Tonsaru, Kecamatan Tondano Selatan, Kabupaten Minahasa, Sulawesi Utara
95618, Indonesia
Email: rahmaniarahman@unima.ac.id

Armin Arif

Program Studi Pendidikan Kimia,
Universitas Megarezky,
Jl. Antang Raya, Kec. Manggala, Kota Makassar, Sulawesi Selatan 90234, Indonesia
Email: arif.armin98@gmail.com

Herwandi

Program Studi Administrasi Kesehatan,
Institut Teknologi dan Kesehatan Permata Ilmu Maros,
Jl. Pallantikan Buttatoa, Kabupaten Maros, Sulawesi Selatan 90516, Indonesia
Email: herwandi@itkpi.ac.id
