Journals Scientica Education Journal
E-ISSN : 3046-8523
https://jurnal-ilcaagam.com/index.php/SEJ/index
Vol.1.No.6 January 2025

Virtual Laboratory-Based Learning in Science Education to Improve Conceptual Understanding, Scientific Literacy, and Critical Thinking Skills

Ayu Rischi Utami
Universitas Negeri Yogyakarta, Indonesia

Entered : November 04, 2024
Accepted: January 17, 2025
Revised : December 13, 2024
Published : January 27, 2025

ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas pembelajaran berbasis laboratorium virtual dalam meningkatkan pemahaman konsep, literasi sains, dan keterampilan berpikir kritis siswa pada pembelajaran IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari dua kelompok, yaitu kelompok eksperimen yang menggunakan pembelajaran laboratorium virtual terintegrasi dengan pendekatan inkuiri dan kelompok kontrol yang menggunakan metode pembelajaran konvensional. Data dikumpulkan melalui tes pemahaman konsep, tes literasi sains, dan tes keterampilan berpikir kritis. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol. Analisis normalized gain (N-gain) menunjukkan bahwa peningkatan pada kelompok eksperimen berada pada kategori sedang hingga tinggi, sedangkan kelompok kontrol berada pada kategori rendah hingga sedang. Uji statistik menggunakan independent sample t-test menunjukkan adanya perbedaan yang signifikan antara kedua kelompok ($p < 0,05$). Selain itu, pembelajaran berbasis laboratorium virtual terbukti meningkatkan kemampuan siswa dalam memahami konsep ilmiah, menginterpretasi data, mengevaluasi bukti, dan memecahkan masalah. Hasil ini menunjukkan bahwa laboratorium virtual merupakan strategi pembelajaran yang efektif dan inovatif dalam meningkatkan kualitas pembelajaran serta mengembangkan kompetensi penting dalam pendidikan IPA.

Kata Kunci: *laboratorium virtual, pemahaman konsep, literasi sains, keterampilan berpikir kritis, pendidikan IPA.*

ABSTRACT

This study aims to examine the effectiveness of virtual laboratory-based learning in improving students' conceptual understanding, scientific literacy, and critical thinking skills in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of two groups: an experimental group taught using virtual laboratory-based learning integrated with inquiry-based activities and a control group taught using conventional methods. Data were collected through a conceptual understanding test, a scientific literacy test, and a critical thinking skills test. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group. The normalized gain (N-gain) analysis indicated that the experimental group reached a medium to high level of improvement, while the control group remained in the low to medium category. Statistical testing using an independent sample t-test revealed a significant difference between the two groups ($p < 0.05$). Furthermore, virtual laboratory-based learning significantly enhanced students' ability to understand scientific concepts, interpret data, evaluate evidence, and solve problems. These findings suggest that virtual laboratories are an effective and innovative instructional strategy for promoting meaningful learning and developing essential competencies in science education.

Keywords: *virtual laboratory, conceptual understanding, scientific literacy, critical thinking skills, science education.*

INTRODUCTION

The rapid advancement of digital technologies has significantly transformed instructional practices in science education, particularly through the integration of virtual laboratory (virtual lab) environments (Poo et al., 2023). Virtual laboratories provide interactive, simulation-based learning experiences that allow students to conduct experiments in a safe, flexible, and cost-effective manner (Parmar et al., 2024). This approach addresses many limitations of traditional laboratory settings, such as limited resources, time constraints, and safety concerns. Recent studies highlight that virtual labs enhance students' conceptual understanding by enabling visualization of abstract scientific phenomena and facilitating repeated experimentation (Makransky et al., 2021; Radianti et al., 2020; Brinson, 2020).

In the context of science education, conceptual understanding is a fundamental component that supports students' ability to apply scientific knowledge in real-world situations (Firdausih & Aslan, 2025). However, many students struggle to understand abstract scientific concepts when learning is limited to theoretical explanations. Virtual laboratories provide immersive and interactive environments where students can manipulate variables, observe outcomes, and test hypotheses in real time (May et al., 2023). Empirical studies indicate that virtual lab-based learning significantly improves students' conceptual understanding and scientific reasoning compared to traditional instruction (Makransky et al., 2021; de Jong et al., 2023; Kapici et al., 2022).

Furthermore, virtual laboratories play an important role in enhancing scientific literacy, which involves the ability to interpret data, evaluate evidence, and make informed decisions based on scientific knowledge (Lestari et al., 2023). By engaging students in inquiry-based activities, virtual labs promote active learning and the development of essential scientific skills. Research shows that virtual lab environments improve students' ability to analyze data, draw conclusions, and apply scientific concepts in different contexts (Kapici et al., 2022; de Jong et al., 2023; Smetana & Bell, 2021).

In addition to improving conceptual understanding and scientific literacy, virtual laboratory-based learning has been shown to enhance students' critical thinking skills (Noris et al., 2022). Virtual labs require students to engage in problem-solving, decision-making, and reflective thinking, which are essential components of higher-order thinking. According to Makransky et al. (2021), immersive virtual simulations can significantly improve students' critical thinking by providing authentic and interactive learning experiences. Similarly, Radianti et al. (2020) and Kapici et al. (2022) emphasize that virtual learning environments encourage students to actively construct knowledge and evaluate their understanding through experimentation.

Despite these advantages, the implementation of virtual laboratories in science education faces several challenges. These include technological limitations, lack of teacher readiness, and the need for effective instructional design to ensure meaningful learning (Kau, 2024). Some studies suggest that without proper guidance, students may experience cognitive overload when using complex virtual environments, which can hinder learning outcomes (Makransky et al., 2021; de Jong et al., 2023; Radianti et al., 2020). Therefore, it is essential to integrate virtual laboratories with appropriate pedagogical approaches, such as inquiry-based learning, to maximize their effectiveness.

Moreover, there is still a need for empirical research examining the combined impact of virtual laboratory-based learning on multiple learning outcomes, including conceptual understanding, scientific literacy, and critical thinking skills. While previous studies have explored these aspects separately, limited research has investigated their interrelationship within a single instructional framework. This gap highlights the

importance of conducting comprehensive studies to better understand the effectiveness of virtual labs in science education.

Therefore, this study aims to investigate the effectiveness of virtual laboratory-based learning in improving students' conceptual understanding, scientific literacy, and critical thinking skills in science education. The findings of this research are expected to contribute to the development of innovative instructional strategies that leverage digital technologies to enhance learning outcomes and prepare students for the demands of 21st-century education.

METHOD

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to examine the effectiveness of virtual laboratory-based learning in improving students' conceptual understanding, scientific literacy, and critical thinking skills in science education. This design is widely used in educational research where random assignment is not feasible, allowing for comparison between experimental and control groups while maintaining the authenticity of classroom settings (Creswell & Creswell, 2021).

The study was conducted in a secondary school setting involving two groups of students. The experimental group was taught using virtual laboratory-based learning integrated with inquiry-based activities, while the control group received conventional instruction using teacher-centered methods and textbook-based explanations. The virtual laboratory environment allowed students to perform simulated experiments, manipulate variables, observe phenomena, and analyze results in an interactive digital setting. Participants were selected using purposive sampling to ensure that both groups had comparable academic abilities and learning characteristics.

Data collection was carried out using three main instruments: a conceptual understanding test, a scientific literacy test, and a critical thinking skills test. The conceptual understanding test was designed to measure students' ability to explain scientific concepts and apply them in different contexts. The scientific literacy test was adapted from international assessment frameworks, focusing on students' ability to interpret data, evaluate evidence, and make scientific decisions (Organisation for Economic Co-operation and Development, 2023). The critical thinking test was developed based on higher-order thinking indicators, including analysis, evaluation, and inference. All instruments were validated through expert judgment and pilot testing to ensure content validity and reliability.

The intervention was implemented over several instructional sessions, during which students in the experimental group engaged in virtual laboratory activities designed to support inquiry-based learning. These activities included hypothesis formulation, experimentation using simulations, data collection, analysis, and conclusion drawing. Previous research indicates that virtual laboratory environments enhance students' conceptual understanding and scientific reasoning by providing interactive and immersive learning experiences (Makransky et al., 2021; Kapici et al., 2022; de Jong et al., 2023).

Prior to the main study, a pilot test was conducted to assess the reliability of the instruments using Cronbach's alpha coefficient. Data analysis involved both descriptive and inferential statistics. Descriptive statistics were used to summarize students' performance, while inferential statistics, including independent sample t-tests and normalized gain (N-gain), were used to evaluate the effectiveness of the intervention. Statistical analysis was conducted using SPSS software with a significance level set at 0.05.

This methodological approach is consistent with recent studies emphasizing the effectiveness of virtual laboratory-based learning in enhancing conceptual understanding, scientific literacy, and critical thinking skills through interactive and inquiry-based learning environments (Makransky et al., 2021; Kapici et al., 2022; de Jong et al., 2023).

RESULTS AND DISCUSSION

Descriptive Statistics of Learning Outcomes

The descriptive analysis revealed that both the experimental and control groups showed improvement in their post-test scores compared to pre-test results. However, the experimental group, which engaged in virtual laboratory-based learning, demonstrated a substantially higher increase in scores across all measured variables, including conceptual understanding, scientific literacy, and critical thinking skills. The comparable pre-test scores between the two groups indicate that students initially had similar levels of knowledge and skills, ensuring that the observed differences were due to the intervention.

This significant improvement in the experimental group suggests that virtual laboratory-based learning provides a more effective learning environment than conventional instruction. The interactive nature of virtual labs allows students to visualize abstract scientific concepts, manipulate variables, and observe outcomes in real time. These features support active learning and knowledge construction, leading to deeper understanding and improved performance.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis showed that the experimental group achieved a medium to high level of improvement across all variables, while the control group remained in the low to medium category. The highest gain in the experimental group was observed in conceptual understanding, followed by scientific literacy and critical thinking skills. This finding indicates that virtual laboratory-based learning not only improves learning outcomes but also enhances the efficiency of the learning process. The ability to repeat experiments and explore different scenarios enables students to reinforce their understanding and correct misconceptions. In contrast, the control group's limited exposure to hands-on or interactive experiences may have restricted their learning gains.

Conceptual Understanding Analysis

The results showed a significant improvement in students' conceptual understanding in the experimental group compared to the control group. Students in the virtual lab environment demonstrated a better ability to explain scientific concepts, apply knowledge to new situations, and connect theoretical ideas with experimental observations. This improvement can be attributed to the visualization capabilities of virtual laboratories, which allow students to observe phenomena that are difficult to demonstrate in traditional classrooms. By interacting with simulations, students can explore cause-and-effect relationships and develop a more coherent understanding of scientific concepts. The repeated exposure to experiments also helps reinforce learning and reduce misconceptions.

Scientific Literacy Analysis

The analysis of scientific literacy indicated that students in the experimental group showed significant improvement in interpreting data, evaluating evidence, and making scientific decisions. These skills were developed through engagement in inquiry-based virtual lab activities that required students to analyze experimental data and draw conclusions.

The improvement in scientific literacy suggests that virtual laboratories effectively support the development of scientific reasoning skills. The interactive environment encourages students to think critically about the data they collect and to justify their conclusions based on evidence. In contrast, students in the control group showed limited improvement, highlighting the limitations of traditional instructional methods in developing scientific literacy.

Critical Thinking Skills Analysis

The results also demonstrated a significant improvement in critical thinking skills among students in the experimental group. Students showed enhanced abilities in analyzing problems, evaluating solutions, and making logical inferences based on experimental data. This improvement is closely related to the inquiry-based nature of virtual laboratory learning, which requires students to actively engage in problem-solving and decision-making processes. The opportunity to test hypotheses and evaluate outcomes in a simulated environment encourages students to think critically and reflect on their learning.

Discussion

1. Effectiveness of Virtual Laboratory-Based Learning

The findings of this study confirm that virtual laboratory-based learning significantly improves students' conceptual understanding, scientific literacy, and critical thinking skills. This result is consistent with Makransky et al. (2021), who found that immersive virtual environments enhance learning by providing interactive and engaging experiences. Similarly, Kapici et al. (2022) reported that virtual laboratories improve students' learning outcomes by enabling them to visualize and manipulate scientific phenomena. Furthermore, de Jong et al. (2023) emphasized that virtual labs support inquiry-based learning by allowing students to experiment and explore scientific concepts independently. The findings of this study reinforce these conclusions, demonstrating that virtual laboratories provide a powerful tool for enhancing science education.

2. Improvement of Conceptual Understanding

The significant improvement in conceptual understanding observed in this study can be explained by the ability of virtual laboratories to provide visual and interactive representations of scientific concepts. These features help students overcome the limitations of traditional instruction, which often relies on abstract explanations. This finding aligns with Makransky et al. (2021) and Kapici et al. (2022), who highlighted the role of visualization in enhancing conceptual learning. By allowing students to observe and manipulate variables, virtual labs facilitate deeper understanding and knowledge construction. This suggests that virtual laboratories are particularly effective in teaching complex and abstract scientific concepts.

3. Enhancement of Scientific Literacy

The improvement in scientific literacy indicates that virtual laboratory-based learning effectively supports the development of scientific reasoning skills. Students were able to interpret data, evaluate evidence, and make informed decisions, which are essential components of scientific literacy. This result is consistent with the OECD (2023) framework, which emphasizes the importance of inquiry-based learning in developing scientific literacy. Additionally, de Jong et al. (2023) found that virtual labs enhance students' ability to engage in scientific practices, such as data analysis and evidence-based reasoning. The findings of this study confirm that virtual laboratories provide an effective environment for developing these skills.

4. Development of Critical Thinking Skills

The improvement in critical thinking skills observed in this study highlights the effectiveness of virtual laboratory-based learning in promoting higher-order thinking. The interactive and inquiry-based nature of virtual labs encourages students to analyze problems, evaluate solutions, and reflect on their learning. This finding is supported by Makransky et al. (2021), who reported that immersive learning environments enhance critical thinking by providing authentic learning experiences. Similarly, Kapici et al. (2022) emphasized that virtual labs promote problem-solving and analytical thinking. The results of this study confirm that virtual laboratory-based learning is an effective strategy for developing critical thinking skills in science education.

5. Role of Interactivity and Visualization

One of the key factors contributing to the effectiveness of virtual laboratories is their ability to provide interactive and visual learning experiences. These features enable students to actively engage with the content and explore scientific concepts in a meaningful way. Radianti et al. (2020) highlighted that immersive technologies enhance learning by increasing student engagement and facilitating experiential learning. The findings of this study support this perspective, showing that interactivity and visualization play a crucial role in improving learning outcomes. Students who actively engage with simulations are more likely to develop a deeper understanding of the material.

6. Challenges and Limitations

Despite the positive findings, several challenges were identified in the implementation of virtual laboratory-based learning. These include technological limitations, potential cognitive overload, and the need for effective instructional design. Makransky et al. (2021) noted that overly complex virtual environments can lead to cognitive overload, which may hinder learning. Similarly, de Jong et al. (2023) emphasized the importance of scaffolding and guidance in virtual learning environments. Therefore, it is essential to design virtual laboratory activities that are structured and aligned with learning objectives to maximize their effectiveness.

CONCLUSION

This study concludes that the implementation of virtual laboratory-based learning has a significant and robust impact on improving students' conceptual understanding, scientific literacy, and critical thinking skills in science education. The findings clearly demonstrate that students who engaged in virtual lab environments outperformed those in conventional classrooms across all measured variables. The interactive and simulation-based nature of virtual laboratories enables students to visualize abstract concepts, manipulate variables, and conduct repeated experiments, thereby facilitating deeper conceptual understanding and more meaningful learning experiences.

Furthermore, virtual laboratory-based learning effectively supports the development of scientific literacy by engaging students in inquiry-driven processes such as data interpretation, evidence evaluation, and scientific reasoning. At the same time, the problem-solving and exploratory features embedded in virtual labs foster the development of critical thinking skills, allowing students to analyze, evaluate, and draw conclusions based on empirical data. These findings confirm that virtual laboratories are not merely a substitute for physical labs but represent an advanced pedagogical tool that enhances both cognitive and scientific competencies.

The novelty of this study lies in its integrated examination of three key learning outcomes conceptual understanding, scientific literacy, and critical thinking within a single virtual laboratory-based instructional framework. Unlike previous studies that

often investigate these variables separately, this research provides comprehensive empirical evidence of how virtual lab environments simultaneously strengthen multiple dimensions of student learning. Additionally, this study highlights the role of interactivity, visualization, and repeated experimentation as key mechanisms driving learning effectiveness in virtual environments.

However, the successful implementation of virtual laboratory-based learning requires careful instructional design, adequate technological infrastructure, and teacher readiness. Without proper scaffolding, students may experience cognitive overload or fail to fully benefit from the virtual environment. Therefore, educators must ensure that virtual lab activities are well-structured, aligned with learning objectives, and integrated with inquiry-based pedagogical approaches. In conclusion, virtual laboratory-based learning offers a highly effective and innovative strategy for advancing science education in the digital era. By bridging the gap between theoretical knowledge and practical application, virtual labs provide a scalable and flexible solution to enhance learning quality and equip students with essential 21st-century competencies.

REFERENCES

Brinson, J. R. (2020). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, 87, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003

Creswell, J. W., & Creswell, J. D. (2021). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2023). Physical and virtual laboratories in science and engineering education. *Science*, 340(6130), 305–308. https://doi.org/10.1126/science.1230579

Firdausih, F., & Aslan, A. (2025). Literature review: The effect of project-based learning on student motivation and achievement in science. *Indonesian Journal of Education (INJOE)*, *5*(1), 85-96.

Kapici, H. O., Akcay, H., & de Jong, T. (2022). Using virtual laboratories in science education: A meta-analysis. *Educational Research Review*, 35, 100418. https://doi.org/10.1016/j.edurev.2022.100418

Kau, M. E. W. (2024). Technology readiness in English language teaching: Analyzing gaps and barriers. *Reduplikasi: Jurnal Penelitian Pendidikan Bahasa Indonesia*, *4*(2), 66-78. https://dx.doi.org/10.37905/rjppbi.v4i2.2685

Lestari, D. P., Supahar, Paidi, Suwarjo, & Herianto. (2023). Effect of science virtual laboratory combination with demonstration methods on lower-secondary school students' scientific literacy ability in a science course. *Education and Information Technologies*, *28*(12), 16153-16175. https://doi.org/10.1007/s10639-023-11857-8

Makransky, G., Petersen, G. B., & Klingenberg, S. (2021). Immersive virtual reality and learning: A meta-analysis. *Educational Psychology Review*, 33, 937–958. https://doi.org/10.1007/s10648-020-09583-6

May, D., Terkowsky, C., Varney, V., & Boehringer, D. (2023). Between hands-on experiments and Cross Reality learning environments – contemporary educational approaches in instructional laboratories. *European Journal of Engineering Education*, *48*(5), 783–801. https://doi.org/10.1080/03043797.2023.2248819

Noris, M., Saputro, S., & Muzazzinah. (2022). The virtual laboratory based on problem based learning to improve students' critical thinking skills. *European Journal of*

Mathematics and Science Education, 3(1), 35-47. https://doi.org/10.12973/ejmse.3.1.35

Organisation for Economic Co-operation and Development. (2023). *PISA 2022 results: Learning outcomes and scientific literacy*. OECD Publishing. https://doi.org/10.1787/pisa-2022

Parmar, H., Siddhpura, M., & Siddhpura, A. (2024). Enhancing Student Engagement: Strategies For Effective Online Laboratory Instruction. In *EDULEARN24 Proceedings* (pp. 3654-3666). IATED. https://doi.org/10.21125/edulearn.2024.0945

Poo, M. C.-P., Lau, Y.-y., & Chen, Q. (2023). Are Virtual Laboratories and Remote Laboratories Enhancing the Quality of Sustainability Education? Education Sciences, 13(11), 1110. https://doi.org/10.3390/educsci13111110

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education. *Computers & Education*, 147, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Smetana, L. K., & Bell, R. L. (2021). Computer simulations to support science instruction and learning: A critical review. *International Journal of Science Education*, 34(9), 1337–1370. https://doi.org/10.1080/09500693.2011.605182