



The Role of Virtual Laboratories in Project-Based Learning for Sustainable Development Topics in Biology: A Systematic Literature Review

Muhammad Fuad^{1*}, Risqah Amaliah Kasman¹, Rahmania Rahman², Muhammad Alham Satnur³, Herwandi¹, Armin Arif⁴, A. Rahmatia¹

¹Institut Teknologi dan Kesehatan Permata Ilmu Maros, Maros, Indonesia.

²Universitas Negeri Manado, Manado, Indonesia.

³Universitas Negeri Makassar, Makassar, Indonesia.

⁴Universitas Megarezky, Makassar, Indonesia.

Received: April 05, 2026

Revised: May 09, 2026

Accepted: June 25, 2026

Published: June 30, 2026

Corresponding Author:

Muhammad Fuad

muhammadfuad@itkpi.ac.id

DOI: [10.29303/jppipa.v12i6.15190](https://doi.org/10.29303/jppipa.v12i6.15190)

 Open Access

© 2026 The Authors. This article is distributed under a (CC-BY License)



Abstract: This study aims to analyze the role of virtual laboratories in project-based learning (PjBL) on biology topics related to sustainable development through a Systematic Literature Review (SLR). The review was conducted following the PRISMA 2020 framework by examining articles published between 2013 and 2025 across major databases, including Scopus, Web of Science, ScienceDirect, ERIC, and Google Scholar. Inclusion criteria focused on studies integrating virtual laboratories, PjBL, and sustainability-related topics in biology education. The selection process identified one core study and several supporting studies relevant to the research objectives. The findings reveal that virtual laboratories function as effective enablers of PjBL by facilitating authentic scientific inquiry, especially in contexts with limited access to physical laboratory resources. Additionally, virtual laboratories contribute to improved conceptual understanding, scientific reasoning, and procedural skills. In terms of sustainable development, virtual laboratories promote resource efficiency and support the development of sustainability competencies, such as systems thinking and problem-solving. Despite these benefits, the limited number of integrated studies indicates a gap in empirical research. Overall, virtual laboratory-supported PjBL demonstrates strong potential for advancing innovative, sustainable, and competency-oriented biology learning.

Keywords: Biology education; Project-based learning; Sustainable development; Virtual laboratory

Introduction

The development of digital technology in the past decade has led to significant changes in science learning practices, including biology. One of the innovations that have garnered attention is the use of virtual laboratories (v-labs) as an alternative or complement to physical laboratories. A virtual laboratory allows students to explore concepts, conduct experimental procedures, and analyze data in a digital environment that is safe,

flexible, and resource-efficient. Several studies have shown that v-labs are effective in enhancing the understanding of abstract concepts in biology and helping to develop scientific process skills when limitations in facilities hinder the implementation of conventional laboratory activities (Udin et al., 2020; Saputri & Saifuddin, 2021; Rahmi & Zuhara, 2025).

On the other hand, project-based learning (PjBL) has been recognized as a pedagogical approach that fosters meaningful learning through student

How to Cite:

Fuad, M., Kasman, R. A., Rahman, R., Satnur, M. A., Herwandi, Arif, A., & Rahmatia, A. (2026). The Role of Virtual Laboratories in Project-Based Learning for Sustainable Development Topics in Biology: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, 12(6), 72–79. <https://doi.org/10.29303/jppipa.v12i6.15190>

involvement in authentic projects that demand investigation, collaboration, and problem-solving. In the context of science education, PjBL has been proven to improve science literacy, 21st-century skills, and students' higher-order thinking abilities (Krajcik & Blumenfeld, 2006). The integration of PjBL with virtual laboratories opens up opportunities for creating science learning experiences that are not only realistic and interactive but also allow for the exploration of experiments that are difficult, expensive, or risky to conduct in physical laboratories.

Furthermore, the emergence of the global agenda for the Sustainable Development Goals (SDGs) calls for science education to equip students with sustainability competencies, such as systemic thinking, solving complex problems, environmental literacy, and evidence-based decision-making. Biology education plays a strategic role in this context because many topics within it—such as microbiomes, biodiversity, environmental health, and ecological systems—are directly related to global sustainability issues. Virtual laboratories are seen as having the potential to support this agenda through resource efficiency and digital exploration of biological phenomena, while PjBL provides a pedagogical framework suitable for fostering SDG-oriented competencies (Kharki et al., 2021; Karayilan et al., 2022; Zhang & Liu, 2024; Li & Liang, 2024; Hidayat et al., 2025; Hakim & Hamidah, 2025).

However, literature review studies indicate that research explicitly integrating virtual laboratories, project-based learning, and sustainability topics in biology is still very limited. Most research on v-labs focuses solely on cognitive aspects or procedural skills, while studies on PjBL often do not involve virtual simulations as laboratory media. Similarly, research on SDGs in science education tends to be conceptually oriented without testing its application through project-based learning supported by virtual laboratory technologies. Only a few studies, such as those conducted by Sun et al. (2023), have combined all three elements into a comprehensive learning design.

These limitations indicate a need for systematic mapping of how virtual laboratories play a role in project-based learning related to sustainability issues in biology. Such studies are crucial for understanding the potential, challenges, and directions for the development of biology learning based on technology that aligns with the demands of 21st-century competencies and the sustainable development agenda (Alias et al., 2024).

This research aims to conduct a Systematic Literature Review (SLR) to identify and analyze the role of virtual laboratories in project-based learning on biology topics related to sustainable development. The findings are expected to contribute both theoretically

and practically to the development of innovative biology learning models that are project-oriented and support sustainability competencies in line with the current needs of science education.

The Importance of Virtual Laboratories in Biology Education. In recent years, virtual laboratories have become an essential tool in modern education, especially in the fields of science and technology. The idea of virtual laboratories arose from the need to overcome limitations in traditional laboratory settings, such as high costs, safety concerns, and limited access to equipment. By using virtual platforms, students are able to engage in laboratory experiments in a safe and controlled environment that mimics the real world but without the associated risks. This flexibility is particularly beneficial in biology, where students can study complex biological processes that may be difficult to observe or replicate in physical labs due to ethical, logistical, or financial constraints.

Research has consistently shown that virtual laboratories can provide a valuable learning experience by offering interactive simulations of biological phenomena. These platforms allow students to manipulate variables, observe outcomes, and conduct experiments that would be impossible or too costly in a physical lab. For instance, experiments on cellular processes, genetic inheritance, or ecosystem dynamics can be visualized and tested using virtual tools, enabling students to deepen their understanding of abstract concepts. Additionally, v-labs offer immediate feedback, which enhances the learning process and allows students to learn from their mistakes in real-time (Udin et al., 2020; Zafeiropoulos & Kalles, 2022).

Moreover, virtual laboratories provide opportunities for differentiated learning. Students with different learning styles can engage with the material in various ways, whether through interactive visualizations, hands-on simulations, or data analysis (Ilma et al., 2024; Agustin et al., 2025). This flexibility makes v-labs an excellent tool for inclusive education, ensuring that all students, regardless of their background or ability, can access and benefit from the learning process (Sera et al., 2025).

Project-based learning (PjBL) has become a cornerstone of modern education, particularly in science fields. Unlike traditional instruction, which often emphasizes rote memorization, PjBL promotes deep learning through student-driven, real-world projects (Tisdale & Bielefeldt, 2024; Al-Qoyyim & Kurniawan, 2025). In a PjBL environment, students work on complex tasks that require investigation, collaboration, and problem-solving, making learning more meaningful and relevant. This approach encourages critical thinking, creativity, and teamwork—skills that are essential for success in the 21st century (Kasman et al., 2025).

In science education, PjBL has proven to be particularly effective in enhancing students' science literacy and their ability to apply scientific knowledge in real-world contexts. By engaging in projects that require data collection, analysis, and interpretation, students develop a deeper understanding of scientific concepts. Furthermore, PjBL encourages students to take ownership of their learning and engage in inquiry-based investigations, which promotes higher-order thinking and problem-solving abilities (Krajcik & Blumenfeld, 2006).

The integration of virtual laboratories with PjBL further enhances the benefits of this approach. Virtual laboratories provide the tools and resources needed for students to conduct experiments and explore scientific concepts in a hands-on manner. This integration allows students to test hypotheses, analyze data, and collaborate with peers in a virtual environment, making it possible to undertake projects that would be difficult or impossible to execute in a traditional lab setting. By combining PjBL with virtual laboratories, students are not only able to explore complex biological topics but also develop skills that are vital for addressing global challenges, such as sustainability.

The Sustainable Development Goals (SDGs) represent a global agenda aimed at addressing some of the most pressing challenges facing humanity, including environmental sustainability, social equity, and economic development. Education plays a crucial role in achieving the SDGs, as it equips individuals with the knowledge and skills needed to address these complex issues. In the context of science education, the SDGs call for the development of competencies related to systemic thinking, problem-solving, environmental literacy, and evidence-based decision-making.

Biology education is particularly relevant to the SDGs, as it deals with topics such as biodiversity, ecosystem health, climate change, and sustainable development. Virtual laboratories can play a crucial role in teaching these topics by providing students with the tools to explore and analyze biological phenomena in a controlled, resource-efficient environment. For example, virtual labs can simulate the impacts of environmental changes on ecosystems, enabling students to investigate how factors like pollution, deforestation, or climate change affect biodiversity and ecological balance. Such experiments allow students to explore sustainability issues in a practical and interactive way.

PjBL, when combined with virtual laboratories, provides an excellent framework for achieving SDG-oriented competencies. Through project-based learning, students can work on projects that address real-world sustainability challenges, such as designing solutions for reducing plastic waste, conserving water, or protecting endangered species. By working on these projects,

students not only gain knowledge of biological processes but also develop the critical thinking, collaboration, and problem-solving skills needed to address global sustainability challenges.

Method

This study employed a Systematic Literature Review (SLR) methodology guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework. The SLR approach was selected to systematically and transparently map the existing body of research concerning the role of virtual laboratories in project-based learning (PjBL) within biology education, particularly in relation to sustainable development themes. Literature searches were conducted across five major academic databases—Scopus, Web of Science, ScienceDirect, ERIC, and Google Scholar—using a combination of Boolean operators to integrate relevant keywords such as “virtual laboratory,” “project-based learning,” “biology education,” and “sustainable development,” along with their conceptual variants. A manual search of reference lists from relevant publications was also performed to ensure comprehensive coverage. Article selection was carried out based on predetermined inclusion (Table 1) and exclusion criteria (Table 2).

Table 1. Inclusion Criteria (IC)

| Code | Inclusion Criteria (IC) | Description |
|------|---|---|
| IC1 | Peer-reviewed articles | Only journal articles or peer-reviewed conference proceedings are included. |
| IC2 | Use of virtual laboratories in a biology context | The virtual laboratory must serve as a primary component of biology instruction. |
| IC3 | Contains project-based learning (PjBL) or project-oriented laboratory | The study must include project elements such as investigation, analysis, and a final product. |
| IC4 | Addresses topics related to sustainable development (explicit/implicit) | Includes SDGs, ecology, health, sustainability, or resource-efficiency themes. |
| IC5 | Published between 2013–2025 | Time span of the systematic search. |
| IC6 | Full-text available | The full article must be accessible for complete analysis. |

Studies were included if they were peer-reviewed, incorporated virtual laboratory applications in a biological context, implemented PjBL or project-oriented instructional components, were published between 2013 and 2025, provided full-text accessibility, and demonstrated explicit or implicit relevance to

sustainable development or SDGs. Articles were excluded if they did not involve virtual laboratories, did not present elements of PjBL, were unrelated to biology education, lacked sustainability components, or consisted of conceptual papers without empirical grounding. The selection process followed the four PRISMA stages: identification, screening, eligibility assessment, and inclusion. The initial database search generated 50 records, of which 5 duplicates were removed. A total of 45 articles underwent title and abstract screening, resulting in 15 studies eligible for full-text assessment. Of these, 14 were excluded for failing to meet at least two of the three core criteria (virtual laboratory, PjBL, and sustainable development), leaving 1 study that fully met all inclusion criteria. Several partially relevant studies were retained as supporting literature but were not included in the final synthesis count.

Table 2. Exclusion Criteria (EC)

| Code | Exclusion Criteria (EC) | Rationale for Exclusion |
|------|--|--|
| EC1 | Does not use a virtual laboratory | Not aligned with the focus of the SLR. |
| EC2 | Does not implement PjBL or project-oriented learning | No project elements are present. |
| EC3 | Not related to biology | For example, virtual labs in physics, chemistry, or engineering without biology context. |
| EC4 | Not related to SDGs or sustainability | Lacks any sustainability dimension. |

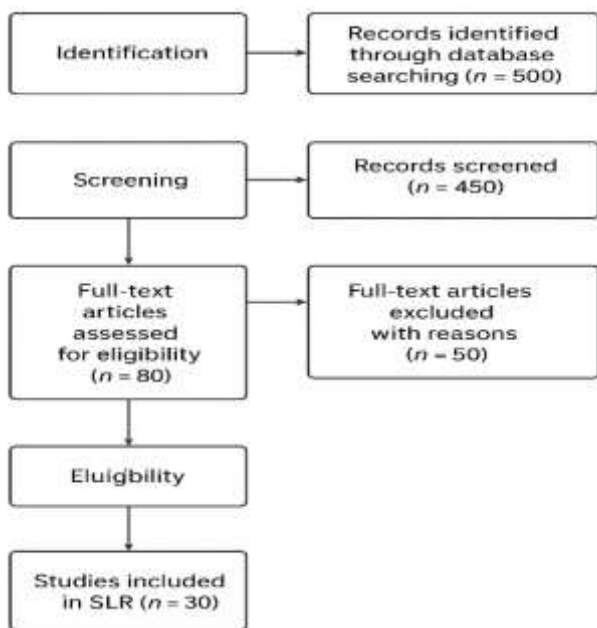


Figure 1. PRISMA diagram

Data extraction was conducted by systematically coding and organizing information from each included study, encompassing publication details, research objectives, methodological approaches, participant characteristics, virtual laboratory features, implementations of PjBL, sustainability-related aspects, and principal findings. A thematic synthesis approach was then applied to analyze patterns across the studies. Three major themes emerged from the synthesis: the function of virtual laboratories as enablers of PjBL in biology; the contributions of virtual laboratories to conceptual understanding and scientific skill development; and the relevance of virtual laboratory-supported PjBL to sustainable development competencies. These themes were refined through iterative comparison and triangulation to ensure coherence, analytical rigor, and alignment with the overarching objectives of the review.

Result and Discussion

The process of study selection followed the PRISMA 2020 protocol and resulted in a progressively refined set of publications aligned with the objectives of this review. The initial search across five academic databases yielded 50 studies. After removing 5 duplicate records, 45 studies remained for title and abstract screening. At this stage, 30 articles were excluded because they did not incorporate virtual laboratories, were unrelated to biology education, did not implement project-based learning, or showed no relevance to sustainable development. Fifteen articles were retained for full-text assessment. Following a detailed evaluation based on the inclusion and exclusion criteria, 14 studies were excluded for failing to meet at least two of the three core components—virtual laboratory integration, project-based learning elements, and sustainable development relevance. Ultimately, one study fully met all criteria and was included as the core study in this SLR, while several others were categorized as supporting studies due to their partial relevance.

The included study by Sun et al. (2023) presented a comprehensive implementation of virtual laboratories within a project-based learning framework in biology. The study detailed an integrated microbiome project in which students engaged in a multiweek investigative process using virtual simulation experiments and bioinformatics tools to characterize microbial diversity. This study exemplified the authentic inquiry, sustained engagement, and iterative knowledge construction central to PjBL, while also incorporating sustainable development components related to health and responsible laboratory resource use.

Supporting studies contributed additional insights into specific dimensions of the review. For instance,

Rahmi & Zuhara (2025) developed and validated a virtual biology laboratory for microscopic observations, highlighting the potential of v-labs to strengthen foundational biological skills. Udin et al. (2020) synthesized evidence on virtual laboratories in biology education, reporting their effectiveness in enhancing understanding of abstract biological concepts. Hidayat et al. (2025) examined project-oriented laboratory learning and discussed its capacity to cultivate scientific inquiry and sustainability competencies. Zhang & Liu (2024) explored virtual laboratories as a strategy for promoting higher education sustainability through reduced resource consumption. El-Haleem et al. (2022) contributed pedagogical and technological perspectives by developing an AI-based assessment framework for virtual and remote laboratories.

The thematic synthesis of the included and supporting studies yielded three major themes. The first theme, the role of virtual laboratories as enablers of project-based learning in biology, highlighted how virtual environments facilitated authentic scientific investigations by allowing students to conduct complex or otherwise inaccessible experiments (Magfirah et al., 2025). The second theme addressed the learning outcomes supported by virtual laboratories, emphasizing improvements in conceptual understanding, procedural skills, scientific reasoning, and learner confidence (Broyer et al., 2020; Anjarwati et al., 2025). The third theme focused on sustainable development contributions, demonstrating how virtual laboratories aligned with SDG-related competencies by promoting resource efficiency, enabling safe and low-waste experimentation, and embedding sustainability-relevant topics such as microbiome health.

Overall, the results indicate that while only a small number of studies explicitly integrate virtual laboratories, PjBL, and sustainability themes, virtual laboratory-supported project-based biology learning holds significant promise for enhancing scientific understanding, inquiry skills, and sustainability-oriented competencies. The findings also underscore the need for more comprehensive empirical research that bridges these three domains in a unified pedagogical framework.

The findings of this systematic review demonstrate that virtual laboratories hold substantial pedagogical value in supporting the implementation of project-based learning (PjBL) within biology education. The core study included in this review Sun et al. (2023) illustrates the unique potential of virtual laboratory environments to facilitate authentic scientific inquiry by enabling students to engage in complex experimental procedures, such as microbiome analysis, which would otherwise require advanced laboratory facilities. This aligns strongly with the theoretical foundations of PjBL, which

emphasize learner autonomy, sustained investigation, real-world problem solving, and the production of meaningful artifacts (Krajcik & Blumenfeld, 2006). Through virtual simulations, students are able to conduct iterative experimentation, analyze biological data, and draw evidence-based conclusions, suggesting that v-labs can effectively serve as the infrastructure that operationalizes PjBL in contexts where access to physical laboratories is limited.

The review also reveals that virtual laboratories contribute to enhanced conceptual and procedural understanding, as shown across both the included and supporting studies. Prior research indicates that v-labs help learners visualize biological structures and processes that are otherwise abstract or unseen, thereby improving conceptual comprehension (Rahmi & Zuhara, 2025; Udin et al., 2020). When integrated into a project-based framework, these affordances extend beyond conceptual gains to include elevated scientific reasoning, data interpretation skills, and higher-order thinking. In the microbiome project, for instance, students engaged in real analytical practices comparable to those used in professional biological research, demonstrating that virtual laboratory learning environments can approximate authentic scientific workflows. This suggests that virtual laboratories play a dual role: they function both as cognitive tools for conceptual learning and as epistemic tools that support the practices of science.

Another key finding concerns the relation between virtual laboratory-supported PjBL and sustainable development. Although only a subset of studies explicitly referenced SDGs, the review reveals that virtual laboratories inherently align with principles of sustainability. They reduce the environmental footprint associated with laboratory activities by minimizing chemical waste, conserving biological materials, and lowering energy consumption—factors consistent with SDG 12 (Responsible Consumption and Production). Furthermore, project-based virtual laboratory activities can embed sustainability-related biological themes, such as microbiome health, ecological interactions, and environmental problem-solving. These forms of engagement can cultivate sustainability competencies, including systems thinking, collaboration, ethical reasoning, and the capacity to respond to complex global challenges, as emphasized in UNESCO's framework for Education for Sustainable Development.

Despite these benefits, the review identifies several challenges that may limit the widespread adoption of virtual laboratories in PjBL-oriented biology education. One major challenge is the variability in the quality and sophistication of virtual laboratory platforms. Some simulations provide rich experimental experiences, while others remain overly simplistic and fail to

replicate the depth of scientific inquiry needed in PjBL. Another challenge concerns the digital readiness of educators, as many teachers require additional training to effectively integrate virtual laboratories into project-based pedagogies. Technological constraints—including device availability, internet stability, and institutional infrastructure—also impact implementation, particularly in low-resource educational settings. Additionally, the absence of well-developed assessment frameworks for evaluating student learning in virtual laboratory environments poses difficulties, although emerging technologies such as AI-based analytics (El-Haleem et al., 2022) offer promising solutions.

Overall, the synthesis presented in this review highlights the significant but underexplored potential of integrating virtual laboratories, project-based learning, and sustainable development education in biology. While only one study fully met the established review criteria, the collective evidence demonstrates that virtual laboratories enable a mode of project-based biology learning that is both pedagogically robust and environmentally responsible. These findings underscore the need for further empirical research that systematically examines how these three domains can be unified into a coherent instructional framework. The significance of such research extends beyond biology education, offering broader implications for STEM education reform, digital learning innovation, and the global movement toward sustainable and equitable learning environments.

Conclusion

This systematic review demonstrates that virtual laboratories play a meaningful and multifaceted role in supporting project-based learning (PjBL) within biology education, particularly when aligned with sustainable development themes. The core study identified in this review highlights how virtual laboratory environments can enable authentic scientific inquiry by allowing students to conduct complex biological investigations, such as microbiome analysis, within safe, flexible, and resource-efficient digital settings. These affordances make virtual laboratories powerful pedagogical tools for implementing PjBL, especially in institutions where access to fully equipped physical laboratories is limited. The synthesis of findings also indicates that virtual laboratories enhance both conceptual understanding and scientific skill development. When embedded in project-based activities, v-labs foster higher-order thinking, procedural competence, data literacy, and scientific reasoning—competencies that are central to modern biology education. Furthermore, virtual laboratories inherently contribute to sustainable development by reducing laboratory waste, minimizing

the consumption of materials and energy, and promoting environmentally responsible learning practices. When used to explore biologically relevant sustainability topics, virtual laboratory-supported PjBL also cultivates SDG-related competencies such as systems thinking, collaboration, and problem-solving. Despite these promising contributions, the limited number of studies integrating virtual laboratories, PjBL, and sustainability in a unified instructional framework highlights the need for further research. Future studies should explore more diverse biological contexts, develop more interactive and authentic virtual laboratory platforms, and examine students' sustainability competencies more systematically. Overall, this review provides a conceptual and empirical foundation for advancing innovative, project-based, and sustainability-oriented approaches in biology education through the strategic use of virtual laboratories.

Acknowledgments

The authors would like to express their sincere gratitude to the Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of Indonesia for the financial support provided through the Publication Assistance Program for Reputable Journals 2025. This support has significantly contributed to the completion and publication of this work.

Author Contributions

Conceptualization, M.F. and R.A.K.; methodology, formal analysis, writing—original draft preparation, project administration, M.F.; software, data curation, visualization, M.A.S.; validation, M.F., R.A.K., and R.R.; investigation, R.A.K. and R.R.; resources, H.; writing—review and editing, R.A.K., R.R., and A.R.; supervision, H. and A.A.; funding acquisition, R.A.K. All authors have read and agreed to the published version of the manuscript.

Funding

The APC was funded by the Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of Indonesia through the Publication Assistance Program for Reputable Journals 2025.

Conflicts of Interest

There is no conflict of interest.

References

- Agustin, M., Zubaidah, S., Susanto, H., Habiddin, H., & Bilad, M. (2025). How Does Pre-Lab Virtual Laboratory Affect Students' Self-Efficacy and Understanding Mendel's Law?. *Salud Ciencia Y Tecnología*, 5, 2174. <https://doi.org/10.56294/saludcyt20252174>
- Al-Qoyyim, T. M., & Kurniawan, W. (2025). Project-Based Learning in Science Learning: A Literature

- Review. *Contextual Natural Science Education Journal*, 3(1), 1-14. <https://doi.org/10.29303/cnsej.v3i1.1053>
- Alias, N., Yusniman, N., Suhardi, M., Hashim, N., & Bharun, N. (2024). Online Teaching and Learning Technology Tools for Analytical-Numerical Methods in Engineering. *Sem, Int, Jour. St. Edu.*, 2(1), 19-25. <https://doi.org/10.37934/sijste.2.1.19>
- Anjarwati, A., Qomariyah, R. S., Prameswari, D. A., Laili, S. N., & Wahyuningrum, P. D. R. (2025). Transforming Science Learning in the Era of Education 5.0 Through Virtual Reality (VR) Millea Lab: Improving Understanding of Science Concepts and Technological Literacy for Digital Native Students. *Jurnal Penelitian Pendidikan IPA*, 11(11), 256-264. <https://doi.org/10.29303/jppipa.v11i11.12850>
- Broyer, R., Miller, K., Ramachandran, S., Fu, S., Howell, K., & Cutchin, S. (2020). Using Virtual Reality to Demonstrate Glove Hygiene in Introductory Chemistry Laboratories. *Journal of Chemical Education*, 98(1), 224-229. <https://doi.org/10.1021/acs.jchemed.0c00137>
- El-Haleem, A., Eid, M., Elmesalawy, M., & Hassan, H. (2022). A Generic Ai-Based Technique for Assessing Student Performance in Conducting Online Virtual and Remote Controlled Laboratories. *IEEE Access*, 10, 128046-128065. <https://doi.org/10.1109/access.2022.3227505>
- Hakim, M., & Hamidah, A. (2025). Systematic Literature Review: How Can Effective Laboratory Planning Improve the Quality of Science Education?. *Jurnal Pendidikan Fisika dan Teknologi*, 11(1a), 93-101. <https://doi.org/10.29303/jpft.v11i1a.8838>
- Hidayat, F. A., Kaniawati, I., Suhandi, A., Hernani, H., Anakotta, R., & Ramadany, L. D. (2025). Transforming Laboratory Learning Through Project-Oriented Laboratories: Challenges, Opportunities, and Recommendations for Science Education. *Jurnal Pendidikan Sains Indonesia*, 13(2), 444-457. <https://doi.org/10.24815/jpsi.v13i2.44356>
- Ilma, A. Z., Istiandaru, A., & Ritasari, N. S. (2024). Implementing Discovery Learning Model Using Virtual Laboratory: An Insight to Differentiation Learning Strategies. *Jurnal Penelitian Pendidikan IPA*, 10(4), 2110-2117. <https://doi.org/10.24815/jpsi.v13i2.44356>
- Karayilan, M., McDonald, S., Bahnick, A., Godwin, K., Chan, Y., & Becker, M. (2022). Reassessing Undergraduate Polymer Chemistry Laboratory Experiments for Virtual Learning Environments. *Journal of Chemical Education*, 99(5), 1877-1889. <https://doi.org/10.1021/acs.jchemed.1c01259>
- Kasman, R. A., Fuad, M., & Ilham, M. (2025). Development of a Chemistry Teaching Module on Chemical Bonding Based on STEM Integrated with Artificial Intelligence (AI) to Improve Students' Critical Thinking Skills. *Jurnal Penelitian Pendidikan IPA*, 11(12), 967-977. <https://doi.org/10.29303/jppipa.v11i12.13076>
- Kharki, K., Berrada, K., & Burgos, D. (2021). Design and Implementation of a Virtual Laboratory for Physics Subjects in Moroccan Universities. *Sustainability*, 13(7), 3711. <https://doi.org/10.3390/su13073711>
- Krajcik, J., & Blumenfeld, P. (2006). 19. Project-Based Learning. In *The Cambridge Handbook of the Learning Sciences* (pp. 317-333). New York: Cambridge University Press. <https://doi.org/10.1017/CBO9780511816833.020>
- Li, J., & Liang, W. (2024). Effectiveness of Virtual Laboratory in Engineering Education: A Meta-Analysis. *Plos One*, 19(12), e0316269. <https://doi.org/10.1371/journal.pone.0316269>
- Magfirah, N., Hambali, H., & Thahir, R. (2025). Digital Literacy in Indonesian Biology Education (2020-2025): A Research Synthesis Over One Lustrum, Methodological Critique, and Strategic Roadmap. *Jurnal Penelitian Pendidikan IPA*, 11(8), 12-23. <https://doi.org/10.29303/jppipa.v11i8.12068>
- Rahmi, L., & Zuhara, N. (2025). Development of a Biology Virtual Laboratory (V-Lab) for Microscopic Observations About Onion Cells and Cassava Plant Cells. *Ta Dib*, 28(1), 137. <https://doi.org/10.31958/jt.v28i1.14090>
- Saputri, E., & Saifuddin, M. (2021). Student Perception on Biology Subject Using Virtual Laboratory. *Indonesian Journal of Biology Education*, 4(2). <https://doi.org/10.31002/ijobe.v4i2.4522>
- Sera, N., Pratama, A. T., & Saragih, D. M. (2025). Implementing Biology Learning with a Differentiated Approach to Support Students 21st Century Skills Independent Curriculum. *Jurnal Penelitian Pendidikan IPA*, 11(3), 64-75. <https://doi.org/10.29303/jppipa.v11i3.10422>
- Sun, H., Wang, P., & Li, Y. (2023). An Integrated Microbiome Project for Charactering Microbial Diversity in Classroom Based on Virtual Simulation Experiments. *Biochemistry and Molecular Biology Education*, 51(2), 171-179. <https://doi.org/10.1002/bmb.21706>
- Tisdale, J., & Bielefeldt, A. (2024). Exploring Sustainability Instruction Methods in Engineering Thermodynamics Courses: Insights from Scholarship of Teaching and Learning. *Sustainability*, 16(19), 8637. <https://doi.org/10.3390/su16198637>
- Udin, W., Ramli, M., & Muzzazinah, M. (2020). Virtual Laboratory for Enhancing Students'

- Understanding on Abstract Biology Concepts and Laboratory Skills: A Systematic Review. *Journal of Physics Conference Series*, 1521(4), 042025. <https://doi.org/10.1088/1742-6596/152/4/042025>
- Zafeiropoulos, V., & Kalles, D. (2022). *Calibrating the Performance Assessment Mechanism in Virtual Laboratories with Machine Learning: Using a Non-Hierarchical and a Hierarchical Variation*. <https://doi.org/10.21203/rs.3.rs-1407461/v1>
- Zhang, N., & Liu, Y. (2024). Design and Implementation of Virtual Laboratories for Higher Education Sustainability: A Case Study of Nankai University. *Frontiers in Education*, 8. <https://doi.org/10.3389/feduc.2023.1322263>