

Virtual Laboratories on Student Engagement: A Systematic Review of Inquiry-Based and Problem-Based Learning Effectiveness

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Abstract: This literature review aims to investigate the impact of virtual labs integrated with Inquiry-Based Learning (IBL) and Problem-Based Learning (PBL) models on student engagement in Science and Physics education. The review examines the effectiveness of applying IBL and PBL models through a systematic literature review, using the PRISMA framework as the protocol. The selected database for this study is SCOPUS, covering the period from 2018 to 2024. The initial screening yielded 1359 articles, of which 20 met the eligibility criteria. This study highlights the paper distribution regarding the virtual laboratories integrating with IBL and PBL showing a positive trend that indicates the field of study has potential for further exploration. Moreover, the study revealed the positive impact on student engagement both from IBL and PBL assisted by Virtual Laboratories.

Article History

Received: 30-07-2024

Revised: 23-09-2025

Published: 30-10-2025

Key Words: Virtual Laboratories, Problem-based Learning, Inquiry-Based Learning, Student Engagement

How to Cite: Faresta, R. A., Ginola, D., Sinambela, I. A. N., & Apriliana, A. (2025). Virtual Laboratories on Student Engagement: A Systematic Review of Inquiry-Based and Problem-Based Learning Effectiveness. *Jurnal Teknologi Pendidikan : Jurnal Penelitian Dan Pengembangan Pembelajaran*, 10(4), 787–798. <https://doi.org/10.33394/jtp.v10i4.12530>

 <https://doi.org/10.33394/jtp.v10i4.12530>

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Introduction

Virtual laboratories have emerged as valuable tools in modern education, providing simulated environments that replicate real laboratory settings and enable students to transform theoretical knowledge into practical skills (Woodfield et al., 2004). Designed with interactive activities, virtual labs offer realistic experimental experiences and serve as effective alternatives to physical laboratories in supporting the learning process (Tiwari & Singh, 2011; Tatli & Ayas, 2013). Teachers today also have access to such technologies to address challenges in science learning that physical laboratories alone cannot resolve (Candelas et al., 2003). Research shows that incorporating virtual laboratories significantly improves student achievement (Tüysüz, 2010; Tatli & Ayas, 2013; Candelas et al., 2003) and fosters positive learning attitudes (Tuysuz, 2010; Candelas et al., 2003; Pyatt & Sims, 2012). Student achievement and attitudes are closely tied to their perceptions of the learning environment (Luketic & Dolan, 2013), and the integration of virtual labs with certain pedagogical models can further enhance their effectiveness (Kadir, 2023). Two models frequently applied are Inquiry-Based Learning (IBL) and Problem-Based Learning (PBL).

IBL emphasizes student-led investigations, encouraging questioning, experimentation, and conclusion-drawing to foster critical thinking and deeper understanding of scientific

concepts (Borkowski, 2024; Casa-Coila et al., 2023). This model not only strengthens conceptual knowledge but also promotes scientific process skills (Ekici & Erdem, 2020). Studies indicate that combining virtual labs with IBL supports the development of scientific thinking, experimental design, and long-term science literacy (Ural, 2016; Wen et al., 2020; Putri et al., 2020; Lefkos et al., 2011; Heradio et al., 2016). Teacher facilitation remains crucial, as proper guidance connects virtual experiments with real-world concepts (de Jong et al., 2013; de Jong et al., 2014). Moreover, inquiry-based virtual labs enhance engagement and science literacy, positively impacting student achievement (Grabau & Ma, 2017; Efstathiou et al., 2018; Chang et al., 2020; Heradio et al., 2016). In contrast, PBL emphasizes solving real-world problems collaboratively, enhancing problem-solving, communication, and teamwork skills (Wisudawati & Eka, 2014; Cahyani & Setyawati, 2016; Bahri et al., 2018). Virtual labs in PBL contexts provide problem-solving-based practicum opportunities that stimulate higher-order thinking and contextualize learning (Sutarno et al., 2017; Cahyani & Setyawati, 2016). This integration supports students' scientific literacy and prepares them to apply knowledge in authentic situations, while simultaneously training critical thinking and intellectual abilities (Bahri et al., 2018).

Despite these advantages, the comparative effectiveness of IBL and PBL when integrated with virtual laboratories remains underexplored. Understanding their respective impacts on student engagement, problem-solving, and scientific literacy is essential for guiding instructional strategies. Therefore, this systematic review aims to synthesize existing research on virtual laboratories combined with IBL and PBL, evaluating their role in enhancing learning outcomes and providing insights for effective implementation in science education.

Research Method

This systematic review was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021; Tülübaş et al., 2023) to examine the impact of virtual laboratories integrated with inquiry-based learning (IBL) and problem-based learning (PBL) on student engagement in physics education. The Scopus database (<https://www.scopus.com>) was selected as the primary source. The review covered publications from 2018 to 2024 using the following keywords: “*Virtual Laboratory integrated with Problem-Based Learning*”, “*Virtual Laboratory integrated with Inquiry-Based Learning*”, and “*Student Engagement*”. The PRISMA framework guided the review across four phases: identification, screening, eligibility, and inclusion. The database selection process is conducted on articles retrieved from the SCOPUS database using the PRISMA framework, which includes the stages of Identification, Screening, Eligibility, and Inclusion.

Selection Process

The literature selection followed a systematic four-stage process. In the identification stage, a database search was conducted using keywords for “Virtual Laboratory integrated with Problem-Based Learning” and “Virtual Laboratory integrated with Inquiry-Based Learning,” covering publications from 2018 to 2024 and including all article types in English to maximize scope. During screening, articles were filtered for relevance, peer review, and alignment with

the study's objectives, with titles and abstracts examined to ensure focus on virtual labs integrated with IBL or PBL. The eligibility stage involved full-text reviews to assess research focus, design, and educational context, retaining only studies that examined the impact of virtual lab integration on student engagement. Finally, the inclusion stage resulted in a set of studies, particularly in physics education, that met all criteria and provided detailed information on authors, study titles, and key findings, forming the evidence base for this review.

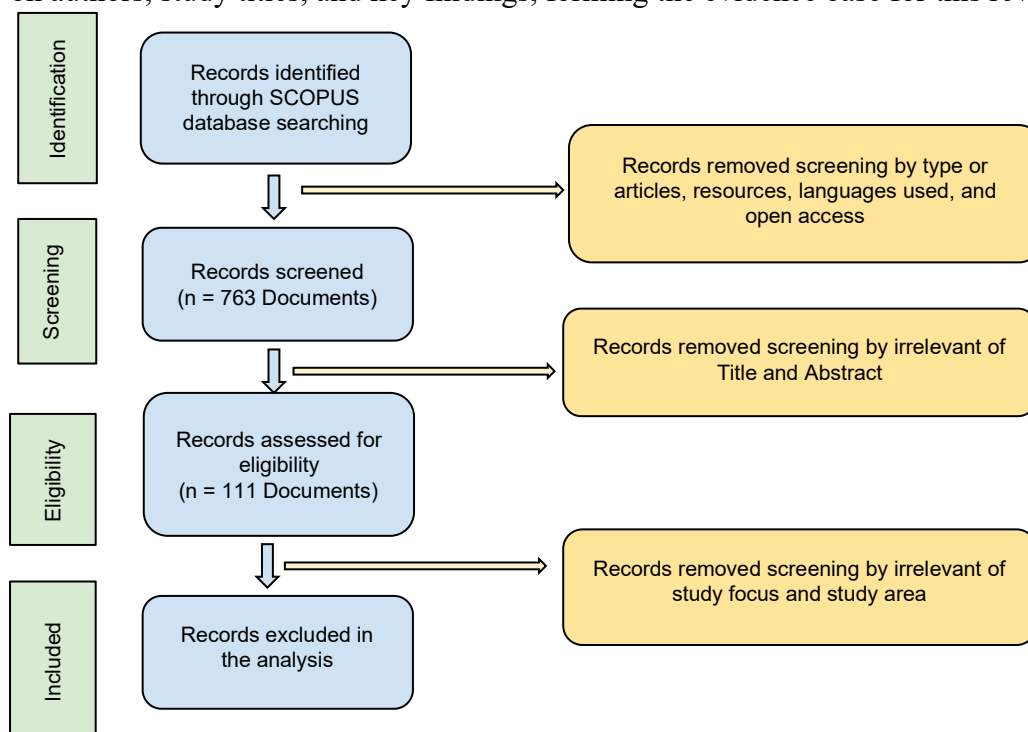


Figure 1. The PRISMA result concerning the keywords of Virtual Laboratory integrated with Problem-Based Learning", "Virtual Laboratory integrated with Inquiry-Based Learning" and "Student Engagement"

Data Analysis

The data analysis focuses on the final database, with qualitative analysis identifying common themes, trends, and gaps in research on virtual laboratories, student engagement, and their integration with inquiry- and problem-based learning. Synthesizing findings highlights effective practices, challenges, and areas for further study, providing insights to inform both practitioners and researchers in technology-enhanced physics education.

Results and Discussion

Using the PRISMA framework, 1,359 articles on integrating virtual labs with inquiry- and problem-based learning (2018–2024) were identified. Initial screening applied eligibility criteria, including peer review, English language, journal source, and open access. Articles were then further evaluated for alignment with the study's objectives, with abstracts and titles assessed for relevance, followed by a full-text review to extract insights and implications for the field.

Paper distribution related to Virtual Laboratory incorporated with IBL and PBL

Articles were searched in the SCOPUS database, focusing on virtual laboratories integrated with inquiry- and problem-based learning. Analysis of publication years (2018–2024), document types, and subject areas provides an overview of research trends in the field.



Figure 2. The distribution paper is based on a virtual laboratory using PBL. (a). documents by year, (b) documents by type, (c) documents by subject area

Figure 2 illustrates the distribution of papers in the field. Figure 2(a) shows an upward trend in studies on virtual laboratories and problem-based learning (PBL) from 2018 to 2023, with 485 papers published, indicating strong academic interest. Figure 2(b) shows that research articles dominate, with 407 publications, highlighting ongoing focus on virtual labs' impact on student engagement. Figure 2(c) reveals the multidisciplinary reach of virtual lab studies, primarily in Social Sciences (36.8%), followed by Computer Science (14.8%), Engineering (10.1%), and Medicine (7.4%).



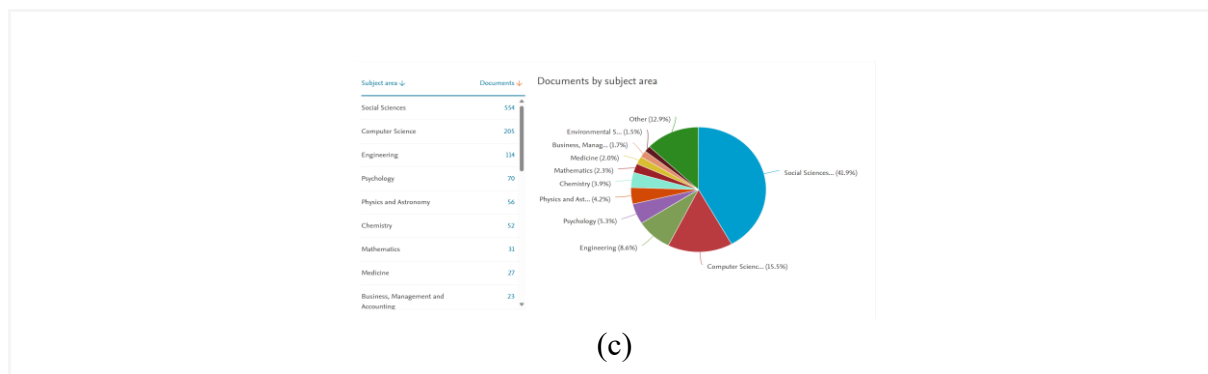


Figure 3. The distribution paper is based on a virtual laboratory using IBL. (a). documents by year, (b) documents by type,(c) documents by subject area

The database search shows a similar trend in research on virtual laboratories integrated with inquiry-based learning (IBL). Figure 3(a) indicates a rise in studies from 2018 to 2023, totaling 631 papers, reflecting strong academic interest. Figure 3(b) shows research articles dominate with 539 publications, highlighting ongoing innovation and focus on student engagement. Figure 3(c) reveals the multidisciplinary nature of virtual lab studies, primarily in Social Sciences (41.9%), followed by Computer Science (15.5%), Engineering (8.6%), and other fields (12.9%).

IBL and PBL embedded Virtual Lab on Student engagement

From the database selection, 20 articles met the inclusion criteria for this literature review. These studies focus on the impact of inquiry- and problem-based virtual labs on student engagement. The analysis highlights each study's findings and identifies common themes and interventions.

Table 1. Data from the existing research related to utilizing Virtual Lab based on IBL

No	Author(s) and Year	Study Highlights
1	Sanchez-Lopez et al., 2024	The study found that immersive virtual reality (IVR) in an analytical biotechnology course positively enhanced student engagement, learning outcomes, motivation, and curiosity, especially in lab-related topics.
2	Susanti et al., 2023	The study shows that integrating virtual programming labs with inquiry-based learning effectively enhances student engagement, particularly in improving higher-order thinking skills in programming courses.
3	Setyowati et al., 2023	The inquiry-based virtual laboratory enhances student engagement by addressing challenges in biology practicums, offering practical activities, and promoting conceptual understanding, especially in the coordination system material.

4	Alhasem Alfailakawi, 2023	& Virtual laboratories integrated with inquiry-based learning significantly enhance student engagement, as shown by positive shifts in attitudes and increased understanding and engagement during physical lab work.
5	Cokar et al., 2021	The virtual laboratory integrated with inquiry-based learning during the COVID-19 pandemic enhanced student engagement by providing flexibility and data analysis opportunities, despite limitations in conducting physical experiments.
6	Kota et al., 2020	The study explores student engagement in virtual labs with inquiry-based learning during COVID-19. It assesses technology integration, inquiry skill development, and modeling understanding in online lab settings.
7	van der Graaf et al., 2020	The integration of virtual labs and informational texts enhances student engagement in inquiry-based learning, as discussed in the paper "Fostering integration of informational texts and virtual labs during inquiry-based learning."
8	Cook , 2022	irtual laboratories integrated with inquiry-based learning, as shown in the study, enhance student engagement by providing additional representations and managing cognitive load effectively, leading to improved learning outcomes.
9	Wahyuman et al., 2021	The impact of Virtual Reality Laboratory on Student Cognitive Engagement is 57.2%, showing positive effects on student learning behavior, aligning with inquiry-based learning principles.
10	Kapici et al., 2022	The study found that a virtual laboratory integrated with inquiry-based learning had a similar impact on student engagement as a hands-on laboratory, benefiting conceptual knowledge and inquiry skills equally.
11	Hohner et al., 2020	The virtual RFID laboratory integrated with inquiry-based learning positively impacts student engagement by providing guidance through experiments, enhancing motivation, and requiring closer alignment between virtual and real experiments.

Recent research highlights the significant benefits of virtual and inquiry-based laboratories (VLs and IVRs) in education, particularly in enhancing student engagement, learning outcomes, and critical thinking skills. Studies consistently show that virtual labs and immersive virtual reality environments positively influence student motivation, engagement, and learning behaviors, especially in laboratory contexts (Sanchez-Lopez et al., 2024; Wahyuman et al., 2021), while inquiry-based virtual labs effectively address practical challenges in biology and chemistry, fostering deeper conceptual understanding (Setyowati et al., 2023; Alhasem & Alfailakawi, 2023). Virtual programming labs integrated with inquiry-based learning further support the development of higher-order thinking, analytical, and

problem-solving skills (Susanti et al., 2023; Cokar et al., 2021; Kota et al., 2020), and their flexibility has been crucial for maintaining educational continuity during the COVID-19 pandemic, accommodating diverse learning styles and student needs.

The integration of virtual labs with informational texts, computer simulations, and video recordings enhances the learning experience by linking theoretical concepts to practical applications and managing cognitive load (Van der Graaf et al., 2020; Cook, 2022). Moreover, appropriate guidance in virtual labs can achieve outcomes comparable to traditional hands-on labs (Kapici et al., 2022), while interactive and guided experiments provide practical benefits such as safety, flexibility, and resource efficiency, alongside improved conceptual understanding (Hohner et al., 2020; Alhasem & Alfalakawi, 2023). Overall, the literature suggests that virtual and inquiry-based laboratories are highly effective educational tools, promoting engagement, learning, critical thinking, and conceptual mastery while offering adaptable and innovative approaches to science education.

Table 2. Data from the existing research related to utilizing Virtual Lab based on PBL

No	Author(s) and Year	Study Highlights
1	Wagino et al., 2024	The integration of a virtual laboratory with problem-based learning enhances student engagement, improves learning outcomes, and fosters critical thinking skills in higher education e-learning ecosystems.
2	Supahar & Widodo, 2021	The integration of Virtual Laboratory with Problem-Based Learning significantly improves student engagement, as shown by the high effect sizes on scientific literacy and problem-solving skills.
3	Xie et al., 2022	The study shows that combining virtual simulation labs with problem-based learning through DingTalk enhances student engagement, promoting better theoretical knowledge and operational skills acquisition.
4	van Hoegen et al., 2021	Problem-based learning integrated with a virtual laboratory enhances student engagement by providing practical experience remotely, aligning with educational levels and fostering self-directed learning during the Covid-19 pandemic.
5	Serungke et al., 2020	The implementation of problem-based learning with a virtual laboratory effectively enhances students' critical thinking skills and learning achievement, indicating increased student engagement through this integrated approach.
6	Elemam et al., 2022	Virtual reality simulation tools integrated with problem-based learning can enhance student engagement in dental education by

refining clinical skills and promoting integrated learning, as proposed in the study.

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| 8 | Nolen & Koretsky,
2018 | Virtual laboratory projects with problem-based learning significantly enhance student engagement compared to physical projects, attributed to the instructional design affordances of the virtual setting. |
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| 9 | Loveys & Riggs,
2019 | The paper discusses integrating online pre-laboratory activities to enhance student engagement. While not explicitly mentioning problem-based learning, the virtual laboratory approach positively impacts student engagement. |
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Recent research underscores the transformative potential of integrating virtual laboratories (VLs) with problem-based learning (PBL) in enhancing student engagement, learning outcomes, and critical thinking across diverse educational contexts. Studies consistently show that this integration fosters greater student involvement and achievement, particularly in scientific literacy and problem-solving skills (Wagino et al., 2024; Supahar & Widodo, 2021; Serungke et al., 2020). The COVID-19 pandemic has further highlighted the value of virtual labs combined with PBL in remote and hybrid learning, demonstrating that virtual simulations and remote lab sessions can maintain or even enhance engagement and learning outcomes under physical distancing constraints (Xie et al., 2022; van Hoegen et al., 2021). This approach is particularly effective in developing higher-order cognitive skills, improving problem-solving abilities, and promoting scientific literacy, which are essential for real-world challenges (Supahar & Widodo, 2021; Serungke et al., 2020).

Additionally, virtual labs support practical experiences and self-directed learning, offering flexibility to accommodate diverse learning needs and contexts (van Hoegen et al., 2021). The integration of technological tools such as virtual reality and simulations with PBL further enhances engagement, refines technical skills, and bridges the gap between theoretical knowledge and practical application (Elemam et al., 2022; Nolen & Koretsky, 2018). Even pre-laboratory activities delivered online contribute to improved engagement and outcomes, emphasizing the value of virtual components in both preparatory and practical learning experiences (Loveys & Riggs, 2019). Overall, the literature highlights that combining VLs with PBL represents an effective, flexible, and innovative pedagogical strategy for modernizing science education.

Conclusion

The evidence consistently demonstrates that virtual and inquiry-based laboratories are highly effective educational tools that significantly enhance student engagement, critical thinking, and learning outcomes. These labs provide flexible, accessible, and interactive environments that address practical challenges and support deeper conceptual understanding. Furthermore, the integration of virtual laboratories with problem-based learning (PBL)

amplifies these benefits by creating a powerful educational strategy. This combined approach not only overcomes the limitations of traditional lab settings but also offers adaptive and effective learning experiences that foster improved student engagement, critical thinking, and academic achievement.

Recommendation

The evidence consistently demonstrates that virtual and inquiry-based laboratories are highly effective educational tools, significantly enhancing student engagement, critical thinking, and learning outcomes. These labs offer flexible, accessible, and interactive environments that address practical challenges and support deeper conceptual understanding. Integrating virtual laboratories with problem-based learning (PBL) further amplifies these benefits, providing a robust strategy that overcomes the limitations of traditional lab settings and delivers adaptive, effective learning experiences. Future research should examine the long-term impacts of these technologies across various disciplines. As educational institutions increasingly adopt digital tools, insights from such studies will be critical for designing engaging and effective learning experiences. Ongoing research and development are essential to optimize these approaches, ensuring they remain adaptable and impactful in diverse and evolving educational contexts.

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