THE INFLUENCE OF STEM ASSISTED BY VIRTUAL LABORATORY MEDIA ON PHYSICS LEARNING: A LITERATURE STUDY

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ABSTRACT

This literature study aims to analyze the influence of the STEM approach assisted by virtual laboratories in physics learning based on the findings of previous studies. The method used is a literature study with a descriptive qualitative approach. Data were obtained from 29 scientific articles relevant to the STEM approach, virtual laboratories, and physics learning within the period 2017-2026. The analysis technique used was content analysis through the identification of patterns of findings, advantages, constraints, and trends in research results. The results of the study indicate that the integration of the STEM approach with virtual laboratories provides the most dominant contribution to improving conceptual understanding, higher-order thinking skills, and students' learning motivation, while also supporting learning outcomes, problem-solving abilities, and student engagement in physics learning. Virtual laboratories help visualize abstract physics concepts through interactive simulations, while the STEM approach encourages students to connect physics concepts with real-world problems contextually. However, the implementation of this learning approach still faces several obstacles, such as limitations in developing real practical skills, teacher readiness, instructional design, and the availability of technological facilities. Therefore, the STEM approach assisted by virtual laboratories can become an effective, interactive, and relevant innovation in physics learning in response to the demands of twenty-first-century learning.

Keywords: STEM, virtual laboratory, physics learning, literature study

INTRODUCTION

Physics learning has an important role in developing students' critical, analytical, and problem-solving abilities. However, physics learning still faces various obstacles, such as limited laboratory facilities, difficulty in understanding abstract concepts, and low student involvement in experimental activities (Pratiwi et al., 2025). Abstract physics concepts require visualization and direct experience; therefore, without appropriate media support, students' understanding becomes less optimal(Kolodii et al., 2025; Mashami et al., 2024). Thus, learning innovations are needed to integrate technology and experimental practice effectively.

The STEM approach (Science, Technology, Engineering, and Mathematics) is one solution for improving the quality of physics learning. This approach emphasizes multidisciplinary integration in solving real problems and developing twenty-first-century skills, such as critical thinking and creativity. Research shows that STEM-based learning can improve higher-order thinking skills through project-based and experimental activities (Wintribrata et al., 2025). This indicates that the STEM approach is relevant for improving the quality of physics learning.

The development of digital technology has introduced innovation in the form of virtual laboratories as an alternative to conventional laboratories. Virtual laboratories allow students to conduct simulated experiments without being limited by equipment and space (Kolodii et al., 2025; Mashami et al., 2024). One study states that "virtual laboratories can democratize access to experimental learning." This shows that virtual laboratories can provide broader and more flexible access to experimental learning for students. The use of virtual laboratories has been proven effective in improving students' learning outcomes and skills. Studies show a significant increase in computational thinking and problem-solving skills after the use of virtual laboratories (Mashami et al., 2024; Meronda, 2025; Pratiwi et al., 2025). In addition, virtual laboratories can improve conceptual understanding through the visualization of physics phenomena that are difficult to observe directly. This makes virtual laboratories an effective learning medium in physics education.

The integration of the STEM approach with virtual laboratories is a highly potential combination in physics learning. This approach emphasizes not only conceptual understanding but also the application of concepts through technology-based digital experiments (Meronda, 2025; Wintribrata et al., 2025). Research shows that the use of STEM-based virtual laboratories can improve students' higher-order thinking skills and science process (Mashami et al., 2024; Wintribrata et al., 2025). Moreover, STEM-based learning with virtual laboratories also increases student engagement and learning motivation. Virtual laboratories enable students to conduct independent exploration, thereby increasing learning activity and conceptual understanding (Kolodii et al., 2025; Mashami et al., 2024; Pratiwi et al., 2025). This is supported by research showing that virtual laboratories provide interactive, flexible, and contextual learning experiences (Meronda, 2025).

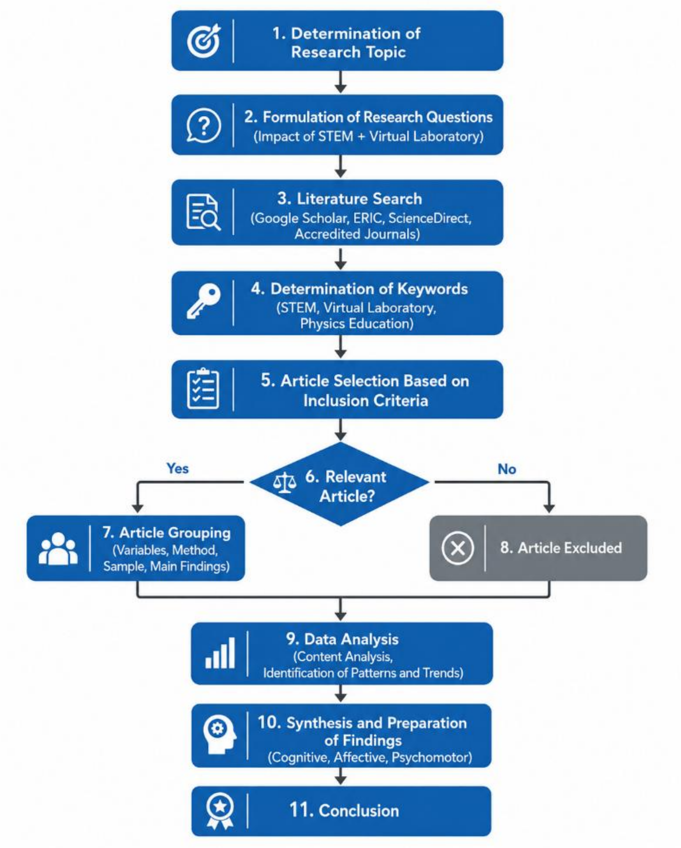
In the context of twenty-first-century education, technology-based learning is an unavoidable need. STEM-based virtual laboratories offer solutions to the limitations of physical laboratories and support distance learning (Kolodii et al., 2025; Meronda, 2025; Pratiwi et al., 2025). In addition, this technology can improve learning quality by providing more realistic and interactive experimental experiences (Wintribrata et al., 2025). Based on this explanation, a comprehensive literature review is needed to analyze the influence of applying STEM with virtual laboratory media in physics learning. This review is important for identifying the effectiveness, advantages, and challenges of implementing this approach (Meronda, 2025). The results of the review are expected to contribute to the development of innovative physics learning models that are relevant to educational technology development.

Although various studies show that virtual laboratories are effective in improving students' learning outcomes and skills, most studies still focus on the use of virtual laboratories separately, without systematic integration with the STEM approach (Kolodii et al., 2025; Meronda, 2025). On the other hand, STEM studies mostly emphasize the development of twenty-first-century skills without exploring in depth the use of virtual laboratories as digital experimental media (Wintribrata et al., 2025). In addition, literature studies that specifically discuss the integration of STEM and virtual laboratories in physics learning remain limited and have not provided a comprehensive picture of their influence on various learning aspects, such as learning outcomes, critical thinking, and science process skills (Mashami et al., 2024; Meronda, 2025). Therefore, a literature study that integrates both aspects comprehensively is needed.

METHOD

The research methodology used in this paper is a literature study with a descriptive qualitative approach. The purpose of this research is to analyze and synthesize various research findings related to the impact of the STEM method (Science, Technology, Engineering, and Mathematics) combined with virtual laboratory media in physics teaching. The research process began with determining the topic and formulating research questions focused on the effects of implementing the STEM method supported by virtual laboratories on learning achievement, critical thinking ability, creativity, problem-solving ability, and students' scientific literacy in physics learning. Next, literature sources were searched through several scientific databases using Publish or Perish and Google Scholar. The keywords used included "virtual laboratory," "virtual laboratory," "STEM approach," and "physics education." The inclusion criteria for this study included articles published within the 2017-2026 period, empirical studies or relevant review articles, articles discussing physics teaching at junior high school, senior high school, or university levels, and articles that clearly discussed STEM integration and/or the application of virtual laboratories. Articles that had no direct relevance to physics teaching or did not provide clear data were excluded from the analysis. The next stage involved selecting and grouping articles based on the variables studied, research methods applied, samples used, and main findings. The data obtained were then analyzed using content analysis techniques by identifying patterns and trends in research findings and comparing findings from various studies to obtain a comprehensive conclusion regarding the impact of the STEM method assisted by virtual laboratories. The synthesis results are presented in a systematic narrative to show the trend of impacts on students' cognitive, affective, and psychomotor aspects in physics teaching. Through this approach, a deep conceptual and empirical understanding is obtained regarding the effectiveness of integrating STEM with virtual laboratory media as an innovation in physics teaching in the digital era.

Figure 1:
Research Method Flowchart



FINDINGS AND DISCUSSION

RESEARCH RESULTS

Based on a synthesis of various studies, the use of virtual laboratories (VLs) in physics education has been shown to have a positive impact on students' conceptual understanding, learning outcomes, and scientific process skills. Virtual laboratories help visualize abstract physics concepts through interactive simulations, making it easier for students to understand the material compared to conventional learning (Banda & Nzabahimana, 2021; Meronda, 2025). Furthermore, research indicates a significant improvement in learning outcomes following the use of virtual laboratories, particularly in topics requiring high levels of visualization such as electricity and waves (Meronda, 2025).

Integrating the STEM approach with virtual laboratories yields more optimal results by combining conceptual understanding with problem-solving skills and higher-order thinking skills (HOTS). STEM-based learning allows students to connect physics concepts to real-world contexts, while virtual laboratories provide flexible digital experimentation tools (Meronda, 2025; Putra et al., 2021). Furthermore, the use of problem-based learning-based virtual laboratories has been shown to enhance critical thinking skills, as students are actively engaged in the processes of exploration, analysis, and drawing conclusions (Banda & Nzabahimana, 2021; Noris et al., 2024)

Several studies indicate that virtual laboratories are more effective at enhancing higher-order cognitive aspects and learning motivation compared to real-world laboratory skills. Furthermore, the success of implementation is significantly influenced by instructional design, teacher readiness, and available technological support (Meronda, 2025; Putra et al., 2021). Therefore, the integration of STEM with virtual laboratories needs to be systematically designed to optimize students' cognitive, affective, and skill-based aspects in physics learning.

Table 1:
Summary of Previous Research on the Integration of STEM and Virtual Laboratory in Physics Learning

No.	Researcher(s) & Year of Publication	Research Title	Method	Findings	Conclusion
1	(Trúchly et al., 2019)	STEM Education Supported by Virtual Laboratory	Experimental	Virtual laboratories increased students' motivation,	Virtual laboratories are effective in increasing

		Incorporated in Self-Directed Learning Process		engagement, and learning outcomes.	engagement in STEM learning.
2	(Ike Lusi Meilina, Asna Azizatur Rohmah et al., 2022)	The Effectiveness of Virtual Laboratory in Physics Learning: A Literature Study	Literature study	Virtual laboratories were effective in improving learning outcomes, motivation, and learning efficiency.	Virtual laboratories are generally effective and efficient in physics learning.
3	(Husnaini & Chen, 2019)	The Effect of Guided Inquiry Virtual and Physical Laboratory on Students' Understanding	Quasi-experimental	Virtual laboratories were more effective for difficult concepts and self-efficacy.	Virtual laboratories are superior in supporting the understanding of complex concepts.
4	(Babalola & Alabi, 2021)	Impact of Virtual Physics Laboratory on Students' Academic Achievement	Experimental	Virtual laboratories improved students' conceptual understanding.	Virtual laboratories are more effective than traditional methods.
5	(Yusuf & Widyaningsih, 2017)	The Implementation of Virtual Laboratory on Critical Thinking Skills	Quantitative	Virtual laboratories improved students' critical thinking skills.	Virtual laboratories have a significant effect on critical thinking skills.
6	Gunawan et al. (2017)	Virtual Laboratory to Improve Students' Problem-Solving Skills	Experimental	Virtual laboratories improved students' problem-solving skills.	Virtual laboratories are effective in improving analytical skills.

7	(Putra et al., 2021)	Student's Perspective on Virtual Laboratory Using PhET Simulation	Mixed method	Virtual laboratories were effective, but students' motivation still needed improvement.	A combination with appropriate learning models is needed for optimal results.
8	Yunzal & Casinillo (2020)	Effect of PhET Simulation on Students' Performance	Quasi-experimental	PhET simulation increased students' learning interest.	Virtual laboratories attract students' attention in learning.
9	El Kharki et al. (2021)	Design and Implementation of a Virtual Laboratory for Physics Subjects in Moroccan Universities	R&D (ADDIE)	Virtual laboratories improved learning outcomes and learning access.	Virtual laboratories support large-scale learning.
10	Rahmi et al. (2022)	Development of a Virtual Lab in Science-Physics Learning Based on the STEM Approach	R&D (4D)	The virtual laboratory was valid and practical to use in learning.	STEM-based virtual laboratories are feasible to use in learning.
11	Maulidah & Prima (2018)	Using Physics Education Technology as Virtual Laboratory in Learning Waves and Sounds	Descriptive	Virtual laboratories improved cognitive aspects and conceptual understanding.	Virtual laboratories help students understand concepts.
12	Ambusaidi et al. (2018)	The Impact of Virtual Lab Learning Experiences	Experimental	Virtual laboratories did not significantly affect learning	Virtual laboratories have a stronger effect on students'

		on Students' Achievement		outcomes, but they produced positive attitudes.	learning attitudes.
13	Widayanti et al. (2019)	Future Physics Learning Materials Based on STEM Education: Analysis of Teachers' and Students' Perceptions	Survey	There is a need to develop STEM-based teaching materials.	STEM learning requires the integration of digital media.
14	Li & Liang (2024)	Effectiveness of Virtual Laboratory in Engineering Education: A Meta-Analysis	Meta-analysis	Virtual laboratories had a significant effect.	Virtual laboratories have a strong impact on learning outcomes and motivation.
15	Callaghan et al. (2020)	Discovery: Virtual Implementation of Inquiry-Based Remote Learning for Secondary STEM Students During the COVID-19 Pandemic	Implementation study	Inquiry-based virtual learning improved students' critical thinking.	Inquiry-based virtual learning can improve higher-order thinking skills.
16	Martyniuk et al. (2021)	Educational Direction of STEM in the System of Realization of Blended	Experimental	STEM and technology integration improved the quality of learning.	The integration of STEM and technology increases learning effectiveness.

		Teaching of Physics			
17	Sellberg et al. (2024)	Virtual Laboratories in STEM Higher Education: A Scoping Review	Review	Virtual laboratories were flexible and effective.	Virtual laboratories are a modern alternative for learning.
18	Apriani et al. (2020)	The Validity of Physics Learning Devices Based on Discovery Learning Model Assisted by Virtual Laboratory	R&D	The learning devices were valid to use.	Virtual laboratories support the development of learning devices.
19	Kapilan et al. (2021)	Virtual Laboratory: A Boon to Mechanical Engineering Education During the COVID-19 Pandemic	Survey	Virtual laboratories improved students' understanding.	Virtual laboratories are effective in distance learning.
20	Mihret et al. (2022)	Effects of Blending Virtual and Real Laboratory Experimentation on Pre-Service Physics Teachers' Attitudes Toward Physics Electricity and	Quasi-experimental	The combination of virtual and real laboratories improved students' learning attitudes.	Blending virtual and real laboratories provides better learning results.

		Magnetism Laboratories			
21	Banda & Nzabahimana (2021)	Effect of Integrating Physics Education Technology Simulations on Students' Conceptual Understanding in Physics: A Review of Literature	Review	PhET simulations improved students' conceptual understanding.	PhET simulations are effective in teaching physics concepts.
22	Samsudin et al. (2020)	The Effect of STEM Project-Based Learning on Self-Efficacy among High-School Physics Students	Quasi-experimental	STEM-PjBL improved students' self-efficacy.	STEM-PjBL increases students' confidence in learning physics.
23	Kolil et al. (2020)	Virtual Experimental Platforms in Chemistry Laboratory Education and Its Impact on Experimental Self-Efficacy	Experimental	Virtual laboratories improved self-efficacy.	Virtual laboratories improve students' confidence and performance.
24	Yang & Baldwin (2020)	Using Technology to Support Student Learning in an Integrated STEM Learning	Review	Technology supported STEM learning.	Technology supports integrated STEM learning environments.

		Environment			
25	Alneyadi (2019)	Virtual Lab Implementation in Science Literacy: Emirati Science Teachers' Perspectives	Qualitative	Virtual laboratories increased motivation.	Virtual laboratories increase students' motivation and engagement.
26	Wintribrata et al. (2025)	Research Trends in Virtual Laboratories Based on STEM in Science Learning and Their Impact on Science Process Skills through Bibliometric Analysis (2020–2024) and the Contribution of Indonesia	Bibliometric	Research trends in STEM-based virtual laboratories increased.	Research on virtual laboratories continues to develop.
27	Akhsan et al. (2023)	Development of a STEM-Based Introduction to Quantum Physics Module on the Sub-Subject of Potential Variations in the Physics Education	R&D	The module was valid and practical.	STEM modules support innovative learning.

		Study Program			
28	Roslina et al. (2022)	Effectiveness of Project-Based Learning Integrated with STEM in Physics Education (STEM-PjBL)	Systematic Literature Review	STEM-PjBL improved cognitive aspects and learning skills.	STEM-PjBL is effective in improving various aspects of learning.
29	Sutaphan & Yuenyong (2019)	STEM Education Teaching Approach: Inquiry from the Context-Based Perspective	Conceptual	STEM inquiry approaches improved problem-solving skills.	Inquiry-based STEM approaches support students' problem-solving skills.

Based on Table 1, most studies indicate that the use of virtual laboratories in physics education has a positive impact on learning outcomes, conceptual understanding, and higher-order thinking skills. Studies using experimental methods, such as those by (Babalola & Alabi, 2021; Trúchly et al., 2019), consistently report improvements in learning outcomes and problem-solving skills following the implementation of virtual laboratories. This suggests that virtual laboratories can serve as an effective alternative to replace or supplement physical laboratories, particularly under conditions of limited facilities.

Quasi-experimental studies such as those by (Husnaini & Chen, 2019; Mihret et al., 2020) show that virtual laboratories are more effective in helping students understand abstract physics concepts compared to conventional teaching methods. This is due to the ability of simulations to visualize phenomena that are difficult to observe directly. On the other hand, development studies such as those by (Apriani et al., 2020; Rahmi et al., 2022) indicate that STEM-based virtual laboratories possess high levels of validity and practicality in learning. There is variation in results across some studies. (Ambusaidi et al., 2018) indicate that improvements in learning outcomes are not always significant in cognitive aspects but are more evident in affective aspects such as motivation and learning attitudes. This suggests that the effectiveness of virtual laboratories is significantly influenced by instructional design, teaching strategies, and student engagement in the learning process.

Table 2:
Ranking Analysis of the Strengths of Previous Research

No	Researcher(s)	Year	Main Advantage
1	Husnaini & Chen	2019	Improving Physics Conceptual Understanding
2	Yunzal & Casinillo	2020	
3	Banda & Nzabahimana	2021	
4	Maulidah & Prima	2018	
5	Babalola & Alabi	2021	
6	El Kharki et al.	2021	
7	Kapilan et al.	2021	
8	Meilina et al.	2023	
9	Gunawan et al.	2017	Improving Higher-Order Thinking Skills (HOTS)
10	Samsudin et al.	2020	
11	Mihret et al.	2022	
12	Sutaphan & Yuenyong	2019	
13	Yusuf & Widyaningsih	2017	
14	Putra et al.	2021	Increasing Learning Motivation and Engagement
15	Trúchly et al.	2019	
16	Alneyadi	2019	
17	Ambusaidi et al.	2018	
18	Widayanti et al.	2019	Supporting STEM-Based Learning
19	Akhsan et al.	2023	
20	Yang & Baldwin	2020	
21	Roslina et al.	2022	
22	Apriani et al.	2020	Development of Learning Media and Learning Devices
23	Rahmi et al.	2022	
24	Kolil et al.	2020	Improving Self-Efficacy and Self-Directed Learning
25	Callaghan et al.	2020	
26	Martyniuk et al.	2021	
27	Li & Liang	2024	Strengthening Theoretical and Empirical Evidence
28	Sellberg et al.	2024	
29	Wintribrata et al.	2025	Indicating Research Development Trends

Based on Table 2, the most prominent advantages identified in previous studies are improved understanding of physics concepts and enhanced higher-order thinking skills. This indicates that the use of virtual laboratories and the STEM approach can help students gain a deeper understanding of complex physics concepts. The improvement in higher-order thinking skills suggests that learning focuses not only on memorization but also on analytical, evaluative, and problem-solving abilities.

Another notable advantage is the increase in student motivation and engagement in learning. Studies such as those by (Putra et al., 2021; Trúchly et al., 2019) show that virtual laboratories provide a more interactive and flexible learning experience, making students more active in the learning process. Additionally, the use of technology in learning can increase students' interest in physics, a subject previously considered difficult.

Beyond cognitive and affective aspects, several studies also highlight advantages in the development of learning media and the enhancement of students' self-efficacy. Research by (Kolil et al., 2020; Samsudin et al., 2020) indicates that STEM-based learning using virtual laboratories can boost students' confidence in completing tasks and solving problems. Nevertheless, these advantages are still largely examined in isolation, thus failing to provide a fully integrated perspective on all aspects of learning.

Based on a synthesis of previous studies, it can be identified that the challenges in physics education are not singular but multidimensional. Dominant issues include limitations in understanding physics concepts, the development of higher-order thinking skills (HOTS), low motivation and engagement in learning, as well as challenges in the development and implementation of technology-based learning media. Additionally, there is a tendency for some studies to still examine these aspects in isolation, thus failing to provide an integrated picture of the effectiveness of the STEM approach combined with virtual laboratories. Therefore, research was categorized based on the main issues identified to obtain a more systematic mapping while revealing remaining research gaps. The results of this categorization are presented in Table 3 below:

Table 3:
Ranking Analysis of Issues in Previous Research

No	Researcher(s)	Year	Main Problem
1	Husnaini & Chen	2019	Physics Conceptual Understanding
2	Yunzal & Casinillo	2020	
3	Ambusaidi et al.	2018	
4	Banda & Nzabahimana	2021	
5	Maulidah & Prima	2018	
6	Babalola & Alabi	2021	
7	Kapilan et al.	2021	
8	El Kharki et al.	2021	
9	Gunawan et al.	2017	Higher-Order Thinking Skills (HOTS)
10	Samsudin et al.	2020	
11	Mihret et al.	2022	
12	Sutaphan & Yuenyong	2019	
13	Yusuf & Widyaningsih	2017	
14	Putra et al.	2021	Learning Motivation and Engagement
15	Trúchly et al.	2019	
16	Alneyadi	2019	
17	Widayanti et al.	2019	Development of STEM Learning
18	Akhsan et al.	2023	
19	Yang & Baldwin	2020	

20	Roslina et al.	2022	
21	Apriani et al.	2020	Development of Learning Media / Devices
22	Rahmi et al.	2022	
23	Kolil et al.	2020	Implementation Limitations
24	Callaghan et al.	2020	
25	Martyniuk et al.	2021	
26	Meilina et al.	2023	Limitations of Literature Studies
27	Li & Liang	2024	
28	Sellberg et al.	2024	
29	Wintribrata et al.	2025	Research Trend Analysis

Based on Table 4, the main issues identified in previous studies relate to students' low understanding of physics concepts and their lack of higher-order thinking skills. This indicates that, despite the development of various instructional innovations, there remains a gap in students' conceptual mastery. These issues are generally attributed to the abstract nature of physics concepts and the lack of instructional materials capable of effectively visualizing these concepts.

Another significant issue is the low level of student motivation and engagement in learning. Several studies, such as those by (Putra et al., 2021; Yunzal, Jr. & Casinillo, 2020), indicate that conventional teaching methods have not been able to optimally capture students' interest. This highlights the need for more interactive and technology-based learning approaches.

The next issue is the limitations in the implementation of technology and the development of learning media. These limitations include a lack of facilities, teacher readiness, and access to technology. Additionally, some studies remain partial and have not comprehensively examined the integration of STEM with virtual laboratories. Therefore, a more integrated approach is needed to simultaneously address these various issues in physics education.

DISCUSSION

When analyzed across studies, improvements in conceptual understanding and higher-order thinking skills are not solely attributed to the use of virtual laboratory media itself, but rather to how such media are integrated into STEM-based learning activities. Virtual laboratories enable students to repeatedly explore variables, test hypotheses, and observe phenomena, which directly fosters the development of scientific thinking processes. In this context, the STEM approach serves as a framework that guides these activities to be more contextual and problem-based, so that students not only understand concepts but are also able to apply them in real-world situations. The effectiveness of learning does not lie in technology alone, but in the interaction between instructional design, exploratory activities, and students' cognitive engagement in constructing knowledge.

The results of this literature study strengthen the relevance of STEM-assisted virtual laboratory learning to the theme of EDUSCIENCETECH 2026, "Innovative Pedagogies for Twenty-First Century Learning: Bridging Theory, Practice and Technology." The integration of STEM and virtual laboratories demonstrates how physics learning can move beyond conventional instruction by combining conceptual theory, technology-based experimentation, and contextual problem-solving activities. This integration allows students to engage in active exploration, analyze scientific phenomena, and develop higher-order thinking skills through digital simulations. Thus, STEM-assisted virtual laboratories can be viewed as an innovative pedagogical approach that bridges theoretical understanding, practical learning experiences, and technological advancement in response to the demands of twenty-first-century learning.

Based on the analysis in Table 1 and Table 2, it is evident that the majority of studies indicate that the use of virtual laboratories in physics education has a significant impact on improving learning outcomes, conceptual understanding, and higher-order thinking skills. Studies using experimental methods, such as those by (Babalola & Alabi, 2021; Trúchly et al., 2019), consistently report significant improvements in learning outcomes and problem-solving skills following the implementation of virtual laboratories. These findings are further supported by quasi-experimental studies such as those by (Husnaini & Chen, 2019; Mihret et al., 2020), which demonstrate that virtual laboratories are more effective in helping students understand abstract physics concepts compared to conventional teaching methods.

However, not all studies show entirely consistent results. Some studies in Table 2 indicate that improvements in learning outcomes are not always significant, as found by (Ambusaidi et al., 2018; Yunzal, Jr. & Casinillo, 2020), where virtual laboratories had a greater impact on affective aspects such as motivation and interest in learning compared to cognitive aspects. Additionally, research by (Putra et al., 2021) also indicates that while virtual laboratories are considered effective and innovative, student learning motivation remains suboptimal. This variation in findings suggests that the success of virtual laboratory implementation is not solely determined by the medium used but also by other factors such as instructional design, teaching strategies, and student engagement in the learning process.

When examining Tables 4 and 5, the comparison between the strengths and limitations of previous studies reveals an interesting pattern. The most dominant strength is the improvement in conceptual understanding and higher-order thinking skills, while the most frequently cited challenges relate to implementation limitations, low motivation, and suboptimal learning outcomes in some studies. This suggests that while virtual laboratories have strong potential to enhance the quality of physics learning, their effectiveness remains contextual and depends on how the medium is integrated into instruction.

A comparison of findings across studies in the table reveals consistency regarding improvements in motivation and engagement, but variations in learning outcomes and conceptual understanding. This suggests that virtual laboratories tend to be more effective at enhancing affective aspects than cognitive ones. Therefore, a more integrated learning approach is needed, such as combining virtual laboratories with inquiry-based STEM approaches or problem-based learning, to optimize all aspects of learning simultaneously.

Based on the synthesis of 29 articles, the integration of STEM approaches with virtual laboratory media in physics learning shows a consistent trend in improving students' conceptual understanding. This is due to the virtual laboratory's ability to visualize abstract physical phenomena more concretely through interactive simulations and direct manipulation of variables. In science education, technology-based visualization has proven effective in helping students understand complex concepts that are difficult to explain conventionally. These findings align with research by (Radianti et al., 2020b), which states that virtual technology can enhance conceptual understanding through immersive learning experiences, and are further supported by (Kefalis et al., 2025), who emphasize that digital simulations play a significant role in modern STEM education. Furthermore, the results of this study are supported by Li & Liang, who demonstrate that virtual laboratories have a strong influence on improving learning outcomes and conceptual understanding.

In addition to enhancing conceptual understanding, the integration of STEM and virtual laboratories also contributes to the development of higher-order thinking skills. The STEM approach encourages students to integrate various disciplines in solving contextual problems, thereby requiring analytical, evaluative, and synthetic skills. Virtual laboratories reinforce this process through simulation-based exploration that allows for independent hypothesis testing and data interpretation. This is supported by (Tene, Marcatoma Tixi, et al., 2024), who demonstrated that the use of digital technology in STEM education significantly enhances critical thinking and problem-solving skills. These findings are also consistent with the results of studies in this review, such as those by Callaghan et al. and Gunawan et al., which demonstrate improvements in higher-order thinking skills through virtual laboratory-based learning. The argument that integrating the STEM approach with virtual laboratory media not only enhances understanding of physics concepts but also strengthens higher-order thinking skills (HOTS) is consistent with the existing literature. Empirical evidence indicates that virtual laboratories support simulation-based exploration, hypothesis testing, and independent data interpretation, all of which contribute to the development of students' analytical, evaluative, and synthetic skills within the context of physics and broader

STEM education (Faqihuddin, 2024; Radianti et al., 2020a; Theasy et al., 2021).

Several specific studies indicate that PhET and similar virtual laboratories can enhance higher-order thinking skills (HOTS) and science literacy when integrated with instructional designs emphasizing structured inquiry, immediate feedback, and real-world contexts (real-world problems) (Faqihuddin, 2024; Theasy et al., 2021). Furthermore, findings regarding the improvement of higher-order thinking skills align with studies reporting that virtual laboratories foster analytical and problem-solving skills through hypothesis testing and data interpretation in a controlled and safe environment (Widiarini et al., 2021).

The link between affective factors and higher-order thinking skills (HOTS) is also supported by the literature, which indicates that affective engagement—such as interest and motivation to learn—can increase when virtual laboratories are combined with inquiry-based instructional design and structured investigative tasks. This increase in affective engagement is often correlated with increased student participation in virtual experiments, thereby fostering higher-order thinking practices and broader science literacy, However, several studies highlight that access to technology, digital literacy, and teacher support remain key mediating factors for the effectiveness of virtual laboratory implementation in both in-person classrooms and distance learning (Faqihuddin, 2024).

Virtual laboratories such as PhET, Olabs, and various virtual-based worksheets have effectively addressed the constraints of accessing real physics labs, increased learning motivation, and facilitated the exploration of physics phenomena safely and cost-effectively, particularly in the context of distance learning or restrictions on real physics labs. Study results indicate that the implementation of STEM-based virtual laboratories consistently improves conceptual understanding, science literacy, and scientific process skills across various educational levels, from secondary school to pre-service physics teacher education. However, this effectiveness is highly dependent on instructional designs that integrate simulations with exploratory activities, conceptual discussions, immediate feedback, and the construction of mental models through guided manipulation of variables (Faqihuddin, 2024; Insana, 2021).

Although it offers various advantages, the findings of this study also indicate several limitations in the implementation o virtual laboratories. One of the main challenges is the suboptimal development of real-world laboratory skills, as virtual laboratories cannot fully replace hands-on experiences in physical laboratories. Additionally, factors such as instructional design, teacher readiness, and access to technology are critical determinants of learning effectiveness. Who state that the effectiveness of virtual learning heavily depends on instructional design and the learning strategies employed, and supported by (Kefalis et al., 2025), who emphasize the importance of pedagogical integration in the use of learning technology.

These findings are also consistent with the research in this study, such as that by Putra et al. and Yang & Baldwin, who affirm that the success of technology use is heavily influenced by pedagogical support. Its effectiveness depends on instructional design, technological infrastructure, and teacher support in guiding students' exploration of concepts and scientific reasoning. These developments align with the findings of (Kefalis et al., 2025; Radianti et al., 2020b) regarding the role of virtual technology and digital simulations in modern STEM learning, as well as with the extensive literature on the positive impact of virtual laboratories on conceptual understanding, science literacy, higher-order thinking skills (HOTS), and scientific process skills, supported by key studies such as those by Li & Liang, PhET, Olabs, as well as inquiry-based and ICI instructional models (Faqihuddin, 2024; Theasy et al., 2021).

The results of the analysis indicate that most previous studies remain limited in scope and have not comprehensively examined the integration of STEM and virtual laboratories. Some studies focus only on a single aspect, such as conceptual understanding, motivation, or media development, and thus do not provide a comprehensive picture of learning effectiveness. Therefore, further research is needed to develop a STEM-based learning model with virtual laboratories capable of simultaneously integrating cognitive, affective, and skill-based aspects. Based on an analysis of relevant literature, previous findings indicate that most studies on the integration of STEM with virtual laboratories are partial and have not comprehensively examined how the combination of the two can simultaneously develop the three dimensions of learning: cognitive, affective, and skills. Many studies focus on only one aspect, such as conceptual understanding, motivation, or media development, so a comprehensive picture of the effectiveness of STEM-based learning with virtual laboratories remains weak when viewed from a broader learning framework (Faqihuddin, 2024; Insana, 2021).

The overall analysis confirms that the integration of the STEM approach with virtual laboratory media has strong potential to improve the quality of physics learning. Findings from various studies indicate positive impacts on improved conceptual understanding, enhanced literacy, and higher-order thinking skills (HOTS), as well as increased student motivation when virtual laboratories are combined with an interactive and contextual STEM approach (Mahardika et al., 2022).

Conceptually, these findings align with the literature framework emphasizing that learning technologies in STEM cannot stand alone; systematic and contextual integration is essential to achieve sustainable and significant impacts on students' cognition, affect, and practical skills. The emphasis on the importance of structured inquiry-based approaches, interactive instructional design, and the use of appropriate feedback aligns with the findings of (Radianti et al., 2020b) regarding the depth of immersive learning experiences through virtual technology, as well as

(Kefalis et al., 2025), who affirm the role of digital simulations in modern STEM education. Furthermore, meta-analyses regarding the effectiveness of virtual laboratories in engineering and technical education also support the view that virtual laboratories contribute significantly to increased motivation, engagement, and higher-order thinking skills, although a balance between virtual and physical laboratory experiences is still needed for certain specific learning contexts (Li & Liang, 2024; Tene, Guevara, et al., 2024)

From a practical classroom perspective, the study's findings also highlight that virtual laboratories effectively address access barriers to physical physics lab facilities, enable distance learning, and provide safe and cost-effective exploration opportunities; however, their implementation heavily depends on the readiness of technological infrastructure and educators' ability to facilitate students' conceptual exploration and scientific reasoning. Therefore, a practical recommendation for educators is to design STEM learning that holistically integrates PhET or other virtual laboratories with interactive worksheets, inquiry tasks, and conceptual discussions to build strong mental models of physics, particularly in real-world contexts and contextual problems. Within a policy framework, the literature also emphasizes the need for infrastructure support, device access, and teacher training to ensure that technology integration serves not merely as a content deliverer but also as a facilitator of critical thinking, scientific literacy, and comprehensive science process skills (Faqihuddin, 2024).

CONCLUSION

Based on a synthesis of 29 articles, the integration of the STEM approach with virtual laboratory media has been shown to have a strong and consistent positive impact on improving the quality of physics learning, particularly in terms of conceptual understanding, higher-order thinking skills, and student engagement. Virtual laboratories play an effective role in facilitating the visualization of abstract physics concepts through interactive simulations, thereby helping students develop a deeper conceptual understanding. Furthermore, the implementation of STEM-based learning combined with virtual laboratories encourages exploratory, analytical, and problem-solving activities, which directly contribute to strengthening students' higher-order thinking skills. Overall, the integration of these two approaches demonstrates significant potential as an innovation in physics education relevant to the demands of the 21st century, particularly in creating learning that is more interactive, contextual, and oriented toward the optimal development of student competencies.

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