ISEJ Indonesian Science Education Journal

ISSN Online: 2716-3350
Vol. 5 No. 2 May 2024 Pages 65-74
https://siducat.org/index.php/isej/
Published by Yayasan Darussalam Bengkulu

The Effectiveness of Virtual Laboratory Media in Physics Education: A Meta-Analysis on Students' Conceptual Understanding and Higher-Order Thinking Skills

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Abstract
The rapid development of information and communication technology has reshaped science education, offering innovative solutions to overcome the limitations of traditional laboratories. In physics, where abstract concepts are often difficult to observe directly, virtual laboratories provide safe, cost-effective, and interactive alternatives for experimentation. This study employed a qualitative meta-analysis supported by descriptive quantitative analysis to synthesize evidence from studies published between 2018 and 2022 on the use of virtual laboratories in inquiry-based physics learning. Data were categorized into achievement indicators such as conceptual mastery, critical thinking, problem-solving, and misconception reduction, and analyzed using descriptive statistics and thematic synthesis. The results indicated a substantial improvement in student performance, with mean scores increasing from 66.42 before intervention to 80.35 afterward, alongside a reduction in achievement gaps across ability levels. Conceptual mastery (25%) and conceptual understanding (20%) were the most frequent outcomes, while higher-order thinking indicators collectively represented 30%. Optics and electricity were the most frequently supported topics, reflecting the strength of simulations in visualizing abstract phenomena. The findings confirm that combining inquiry pedagogy with virtual laboratories yields stronger learning outcomes than either approach alone. This study implies that virtual laboratories can democratize access to experimental learning while fostering essential 21st-century competencies in resource-limited educational contexts.

Keywords: Conveptual Mastery; Higher-Order Thinking Skills; Inquiry-Based Learning; Physics Education; Virtual Laboratory.

INTRODUCTION

The rapid advancement of science and technology in the 21st century has brought profound implications for education, particularly in the teaching and learning of physics. The integration of Information and Communication Technology (ICT) has transformed educational practices, offering new opportunities for active and meaningful learning experiences (Ertmer & Ottenbreit-Leftwich, 2010; Irawansyah & Barata, 2024; König et al., 2020; Lucas et al., 2021; Wahyuni & Irwandani, 2024). Physics, as a discipline grounded in conceptual reasoning and empirical validation, requires not only the mastery of abstract knowledge but also its application in experimental contexts. However, conventional laboratory-based practices in schools remain constrained by limited resources, safety issues, and financial barriers, making it difficult for students to consistently engage in hands-on experimentation (Rizman Herga et al., 2016; Santos & Prudente, 2022; Werth et al., 2022). To address these challenges, virtual laboratories have emerged as an innovative pedagogical approach that allows students to simulate real experiments in a safe, cost-effective, and interactive environment.

Virtual laboratories can be defined as digital multimedia platforms that integrate text, images, animations, video, and interactive simulations to replicate laboratory experiences (Abdulwahed & Nagy, 2014; Maulidah & Prima, 2018; Potkonjak et al., 2016; Ray & Srivastava, 2020). They provide learners with opportunities to conduct experiments that may otherwise be too dangerous, costly, or impractical in traditional laboratory settings (Rosli & Ishak, 2024; Soraya et al., 2022; Uwitonze & Nizeyimana, 2022). Research has consistently demonstrated that virtual laboratories contribute positively to enhancing conceptual understanding, improving problem-solving skills, and reducing misconceptions in science learning (Abdelmoneim et al., 2022; Husnaini & Chen, 2019; P. Dela Cruz et al., 2025; Soraya et al., 2022). Moreover, such tools align with inquiry-based learning paradigms, in which students actively construct knowledge by asking questions, testing hypotheses, and analyzing results (Hmelo-Silver et al., 2007; Minner et al., 2010; Pedaste et al., 2015). This synergy between inquiry pedagogy and digital simulation technology has been shown to foster deeper learning outcomes and higher-order thinking skills (HOTS) in physics education (Aktaş & Karamustafaoğlu, 2024; Antonio & Prudente, 2023).

Despite the proven benefits of virtual laboratories, several challenges persist in their implementation. Some studies indicate that while virtual laboratories enhance students' conceptual mastery, they may not fully replicate the collaborative and affective dimensions of traditional laboratory work (Elmoazen et al., 2023; Reyes et al., 2024). Furthermore, differences in students' digital literacy, motivation, and self-regulation may affect the extent to which virtual laboratories can improve learning outcomes (Ernita et al., 2024; Getenet et al., 2024; Sui et al., 2024). Another issue concerns the specific areas of physics that are most effectively taught using virtual simulations. While topics such as optics, electricity, and thermodynamics are frequently addressed through simulation, less is known about how virtual laboratories can support more complex or abstract concepts such as electromagnetism or quantum phenomena (Castro-Gutiérrez et al., 2023; Dengel & Magdefrau, 2020; Migdał et al., 2022; Tarng & Pei, 2023). This inconsistency in the literature highlights the need for a comprehensive synthesis of findings across multiple studies.

A further concern lies in the variation of instructional designs accompanying virtual laboratories. Some researchers emphasize the importance of embedding simulations within structured inquiry-based frameworks to maximize learning benefits (Flegr et al., 2023; Siantuba et al., 2023; Simbolon & Silalahi, 2023). Others argue that unguided exploration may limit students' engagement and conceptual development (Hmelo-Silver et al., 2007; Kirschner et al., 2006; Lazonder & Harmsen, 2016). These contradictions indicate a gap in understanding how inquiry-based learning strategies interact with virtual laboratories to promote deeper learning and higher-order thinking skills. Moreover, most existing studies tend to focus on small-scale classroom interventions, leaving a lack of meta-analytic evidence that systematically evaluates the overall effectiveness of virtual laboratories in physics education.

Given these issues, this study seeks to address the gap by conducting a meta-analysis on the implementation of virtual laboratories in physics learning, with particular attention to their impact on students' conceptual understanding and higher-order thinking skills. Unlike previous studies that examined isolated cases, this research synthesizes evidence across multiple contexts to provide a comprehensive perspective on the pedagogical potential of virtual laboratories. The novelty of this study lies in its dual focus on conceptual mastery and higher-order thinking, which are both essential for preparing students to meet the cognitive demands of modern science education. The objectives of this research are twofold: (1) to evaluate the extent to which virtual laboratories improve student competence in physics learning, and (2) to identify the indicators and subject areas where virtual laboratories are most effective. Through this approach, the study aims to contribute theoretically to the discourse on digital pedagogy and practically to the design of more effective technology-enhanced learning strategies in physics education.

METHODS

This study adopted a qualitative meta-analysis design complemented by descriptive quantitative analysis to investigate the effectiveness of virtual laboratories in physics education. Meta-analysis was selected because it allows systematic synthesis of evidence across multiple studies, providing a comprehensive understanding of the impact of virtual laboratory integration on students' conceptual mastery and higher-order thinking skills (HOTS). The data sources included peer-reviewed journal articles published between 2018 and 2022 that explicitly examined the use of virtual laboratories in physics learning. Articles were retrieved using academic databases such as Scopus, Google Scholar, and ScienceDirect, with the inclusion criteria focusing on studies that (1) implemented virtual laboratories as a learning medium, (2) measured outcomes related to conceptual understanding, problem-solving, critical thinking, or misconception reduction, and (3) employed inquiry-based learning as the pedagogical framework. Exclusion criteria included studies that lacked empirical data, did not report clear outcomes, or used non-physics contexts.

The research procedure followed three main stages: identification, screening, and coding. In the identification phase, an initial pool of 56 articles was collected. After applying the inclusion and exclusion criteria, 22 articles were retained for further analysis. During the screening stage, each study was evaluated based on its methodological rigor, relevance to physics education, and reported learning outcomes. In the coding process, variables were categorized into ten dependent indicators: conceptual mastery, conceptual understanding, critical thinking, problem-solving, misconception reduction, scientific argumentation, psychomotor and affective skills, conceptual change, learning outcomes, and learning interest. Each variable was coded using a binary scoring system (presence/absence) and frequency counts, which were later converted into relative percentages.

Quantitative data were analyzed using descriptive statistics, specifically calculating the mean, maximum, and minimum scores from pre- and post-intervention studies. These data provided a measurable overview of learning gains associated with virtual laboratory implementation. Meanwhile, qualitative synthesis was applied to identify recurring patterns, thematic consistencies, and pedagogical strategies employed across the selected studies. The integration of quantitative and qualitative approaches ensured a more robust and comprehensive analysis, consistent with mixed-methods recommendations for meta-analytical research (Fetters & Freshwater, 2015; Johnson et al., 2007).

RESULTS AND DISCUSSION

Improvement of Student Achievment

The statistical analysis of students' performance revealed a remarkable improvement in learning outcomes following the integration of virtual laboratories within inquiry-based learning environments. As presented in Table 1, the mean pre-test score was 66.42, which increased significantly to 80.35 in the post-test. This 13.93-point improvement reflects not only a quantitative gain but also a qualitative shift in students' engagement with physics learning. Moreover, the reduction in score variability, from a wide range of 55–75 in the pre-test to a narrower distribution of 70–85 in the post-test, demonstrates that the intervention benefitted students across diverse ability levels. This narrowing of achievement gaps suggests that virtual laboratories provide equitable access to learning resources, enabling both high-achieving and lower-achieving students to engage meaningfully with abstract concepts in physics.

Table 1. Comparison of Student Scores Before and After Intervention

Measurement	Mean Score	Highest Score	Lowest Score
Pre-Test (Before Inquiry)	66.42	75	55
Post-Test (After Inquiry)	80.35	85	70

These findings resonate strongly with previous research. Cheng & Tsai (2019) demonstrated that students who engaged with simulation-based laboratories achieved significantly higher scores in science subjects compared to those in traditional settings, underscoring the potential of digital tools to promote deeper learning. Similarly, Makransky et al. (2019) highlighted that immersive virtual laboratories support equitable learning gains by leveling the playing field for students with different prior experiences. In line with these results, Roca-Hurtuna et al. (2021) also reported that students using virtual simulations in physics classrooms showed sustained improvement in conceptual mastery and retained knowledge more effectively over time.

The improvement observed in this study can also be attributed to the inquiry-based nature of the intervention. Inquiry-based learning encourages students to actively explore, question, and construct their own knowledge, thereby fostering higher-order thinking skills (Hmelo-Silver et al., 2007; Pedaste et al., 2015). When integrated with virtual laboratories, inquiry allows students to simulate experiments, manipulate variables, and observe immediate outcomes—opportunities that may be difficult to replicate in resource-limited physical laboratories. This combination not only enhances conceptual understanding but also strengthens critical thinking, problem-solving, and scientific reasoning, all of which are essential skills for the 21st century (Freeman et al., 2014; Wieman, 2014).

Furthermore, the narrowing of score disparities suggests that virtual laboratories have an inclusive effect, enabling learners from different backgrounds to access the same experimental experiences regardless of resource constraints. This aligns with findings from Cheng and Tsai (2019) who emphasized that digital learning tools reduce inequities in science classrooms by offering uniform learning opportunities. Such inclusivity is particularly important in physics, where access to laboratory infrastructure is often uneven across schools.

Taken together, these findings highlight that virtual laboratories, when embedded in inquiry-based learning, not only improve academic outcomes but also democratize access to meaningful science education. The improvement in mean scores, coupled with the reduced variability, provides compelling evidence that technology-enhanced inquiry learning environments can effectively bridge achievement gaps, support diverse learners, and foster higher-order competencies required in modern science education.

Analysis of Learning Indicators

The analysis of achievement indicators revealed important insights into the types of competencies most enhanced by the integration of virtual laboratories with inquiry-based instruction. As shown in Table 2, conceptual mastery accounted for the highest proportion of outcomes at 25%, followed by conceptual understanding at 20%. Together, these two categories indicate that virtual laboratories are particularly effective in reinforcing foundational knowledge structures and enabling students to apply physics concepts in new contexts. Moreover, higher-order thinking indicators including critical thinking, problem-solving, and misconception reduction collectively represented 30% of the coded data, demonstrating that virtual laboratories also play a crucial role in promoting cognitive skills beyond factual recall.

Table 2. Distribution of Achievement Indicators

Indicator	Frequency	Relative Percentage
Conceptual Mastery	5	25%
Conceptual Understanding	4	20%
Critical Thinking	2	10%
Problem-Solving	2	10%
Misconception Reduction	2	10%
Scientific Argumentation	1	5%
Psychomotor & Affective Skills	1	5%
Conceptual Change	1	5%
Learning Outcomes	1	5%
Learning Interest	1	5%

The predominance of conceptual mastery as the highest indicator aligns with research by Brown & Ryoo (2008), who reported that virtual simulations facilitate direct observation of physical phenomena, thereby improving conceptual retention and transfer. Similarly, Hu et al. (2016) found that virtual laboratories reduce the persistence of misconceptions by allowing learners to repeatedly test hypotheses in safe, low-cost environments. Cheng & Tsai (2019) further emphasized that virtual laboratories enhance not only understanding but also motivation, which indirectly supports the consolidation of concepts. This suggests that the improvement in conceptual mastery observed here is not an isolated outcome but part of a broader pattern documented across multiple studies.

The strong representation of higher-order thinking indicators is also noteworthy. Critical thinking and problem-solving collectively reached 20%, while misconception reduction accounted for an additional 10%. These results resonate with findings by Ernita et al. (2024) and Makransky et al. (2019), who highlighted that inquiry-oriented digital environments nurture students' ability to analyze, evaluate, and synthesize scientific information. Furthermore, Freeman et al. (2014)

showed that active learning strategies, such as those embedded in inquiry-based virtual laboratories, significantly improve problem-solving performance and reduce failure rates in STEM disciplines. The current study reinforces these claims by demonstrating that virtual laboratories are not only tools for knowledge acquisition but also powerful platforms for cultivating HOTS.

The smaller but still significant contributions of indicators such as scientific argumentation (5%), conceptual change (5%), and affective or psychomotor skills (5%) also merit discussion. These outcomes, though less frequent, reflect the multidimensional benefits of virtual laboratories. For example, Cheng and Tsai (2019) argued that digital simulations support collaborative learning and scientific discourse by providing students with shared, observable data sets to discuss and interpret. Similarly, Rosli and Ishak (2024) noted that virtual laboratories encourage positive attitudes toward science, thereby enhancing affective engagement and long-term interest. While these indicators represent a smaller percentage of the overall distribution, they highlight the holistic impact of virtual laboratories on both cognitive and non-cognitive domains of learning.

Another important observation concerns the role of virtual laboratories in misconception reduction. Physics education is widely recognized for its persistent conceptual difficulties, such as misunderstandings of optics, forces, or energy (McDermott & Redish, 1999). The 10% representation of misconception reduction in this study indicates that simulations provide corrective feedback that helps learners resolve inconsistencies between their prior beliefs and observed phenomena. This finding aligns with Mayer (2014), who argued that interactive learning tools enhance conceptual change by confronting students with visual representations that challenge intuitive but incorrect models.

Taken together, these results suggest that virtual laboratories, when combined with inquiry-based pedagogy, function as more than substitutes for physical laboratories. They serve as cognitive scaffolds that reinforce conceptual mastery, promote higher-order thinking, and foster positive engagement with science learning. The distribution of achievement indicators highlights that while conceptual mastery is the most immediate outcome, the broader contribution lies in cultivating critical inquiry skills and reducing misconceptions—both of which are essential for preparing students to meet the complex demands of modern science and technology.

Subject Matter Distribution in Physics Learning

An analysis of the subject matter most frequently addressed through virtual laboratories highlights the types of physics topics where digital simulations offer the greatest pedagogical benefits. As presented in Table 3, optics and instruments emerged as the most frequently supported area, representing 20% of all identified materials. This was followed by momentum and impulse, elasticity, electricity, and heat, each accounting for 10%. Less frequent but still notable topics included reaction rate, fluid dynamics, electromagnetic waves, heat transfer, simple harmonic motion, and Faraday's induction law, each comprising 5%.

Table 3. Physics Topics Supported by Virtual Laboratories

Physics Topic	Frequency	Relative Percentage
Optics and Instruments	4	20%
Momentum and Impulse	2	10%
Elasticity	2	10%
Electricity	2	10%
Heat	2	10%
Reaction Rate	1	5%
Fluid Dynamics	1	5%
Electromagnetic Waves	1	5%
Heat Transfer	1	5%
Simple Harmonic Motion	1	5%
Faraday's Induction Law	1	5%

The dominance of optics in this distribution is unsurprising given its inherently abstract and visual nature. Phenomena such as reflection, refraction, lens behavior, and image formation are difficult to observe without specialized equipment, making them well suited for virtual simulations. This aligns with Cheng and Tsai (2019), who found that optical experiments conducted via simulations improved students' conceptual understanding and reduced misconceptions about light behavior. Similarly, Hu et al. (2016) demonstrated that virtual optics experiments foster deeper learning by allowing learners to manipulate variables such as light intensity and angle of incidence in real time.

Electricity and heat, which together accounted for 20% of the topics, also benefited from virtual laboratory use. Prior research by Stein et al. (2015) confirmed that virtual simulations of electric circuits enhanced students' problem-solving abilities and conceptual transfer to real-world contexts. In the case of thermodynamics, Cheng and Tsai (2019) highlighted that simulations enabled learners to visualize particle behavior and energy transfer processes that are otherwise invisible in physical laboratories. The present findings extend these results by confirming that electricity and thermodynamics remain among the most frequently taught topics with digital simulations, underscoring their continued relevance in modern physics pedagogy.

Momentum, impulse, and elasticity, each representing 10%, also indicate the potential of virtual laboratories to support mechanics learning. These topics often involve dynamic processes that are difficult to replicate with physical equipment due to safety, cost, or time constraints. Studies by Roca-Hurtuna et al. (2021) similarly emphasized that virtual simulations enable repeated, risk-free experimentation, thereby enhancing students' understanding of motion, forces, and material properties.

Although less frequently reported, subjects such as fluid dynamics, electromagnetic waves, heat transfer, simple harmonic motion, and Faraday's law of induction each accounted for 5%. These findings are significant as they point to an underutilization of virtual laboratories in areas that are equally abstract and conceptually demanding. Research by Freeman et al. (2014) and Makransky et al. (2019) indicated that simulations of electromagnetic phenomena and oscillatory motion are highly effective in bridging the gap between mathematical representations and physical intuition. The low frequency of these topics in the analyzed data suggests a gap in practice that future research and instructional design could address.

Overall, the distribution of subject matter reveals that virtual laboratories are predominantly employed in domains requiring visualization of abstract or microscopic phenomena. This trend is consistent with the theoretical framework of cognitive load reduction Mayer (2014), which posits that multimedia simulations alleviate cognitive overload by presenting information in multiple modalities. The implication for educators is clear: while optics and electricity remain priority areas for simulation-based learning, broader adoption across mechanics, electromagnetism, and thermodynamics could further enhance physics education by enabling more comprehensive coverage of challenging concepts.

Comparative Analysis, Novelty, Implications, and Limitations

The results of this study align with and extend existing findings on the role of virtual laboratories in physics education. Previous research has consistently shown that digital simulations enhance conceptual understanding, reduce misconceptions, and promote student engagement. For instance, Brown and Ryoo (2008) reported that virtual laboratories contribute significantly to conceptual change by helping students overcome persistent misconceptions in physics. Similarly, Stein et al. (2015) emphasized that simulations embedded in inquiry-based learning environments improve scientific reasoning and foster deeper understanding, which resonates with the present study's findings on the improvement of higher-order thinking skills. Hu et al. (2016) also demonstrated that virtual laboratories enhance motivation and problem-solving abilities, which parallels the gains observed in critical thinking and problem-solving indicators in this research. In addition, Makransky et al., (2019) argued that virtual environments provide equitable learning opportunities by reducing variability in student achievement, a claim that is corroborated by the reduced score range between pre- and post-tests in this study. Moreover, Roca-Hurtuna et al. (2021) and Janbooranapinij et al. (2022) showed that virtual laboratories facilitate long-term retention and the transfer of abstract physics concepts into real-world contexts, reinforcing the present results that highlight optics as the most effectively supported subject area.

While these consistencies strengthen the reliability of the findings, the current study extends the literature by offering a meta-analytic perspective that synthesizes results across multiple contexts rather than focusing on isolated classroom interventions. This novelty lies in the integration of inquiry pedagogy with virtual laboratory use, demonstrating that their combination yields stronger improvements in conceptual mastery and higher-order thinking skills compared to using virtual laboratories alone. The study also highlights that specific domains of physics, such as optics and electricity, particularly benefit from virtual simulations, offering nuanced insights for educators in selecting appropriate topics for technology-enhanced instruction. The theoretical implication of this research is the reinforcement of digital pedagogy frameworks that couple inquiry-based learning with virtual simulations as a powerful strategy for promoting active engagement and deeper cognitive development. Practically, the findings suggest that virtual laboratories represent a cost-effective and scalable solution for schools with limited physical laboratory infrastructure, enabling safe and efficient experimentation while fostering 21st-century skills such as problem-solving, scientific reasoning, and creativity.

Despite its contributions, this study acknowledges several limitations. First, the analysis was confined to studies published between 2018 and 2022, which may restrict the comprehensiveness of the evidence base by excluding earlier or unpublished works. Second, the reliance on secondary data limits control over variations in instructional design, classroom context, and sample diversity, thereby affecting the generalizability of results. Third, the dominance of optics-related topics in the analyzed studies may bias the conclusions toward subject areas that naturally lend themselves to visualization, while the effectiveness of virtual laboratories in more abstract or mathematically intensive topics remains underexplored. Future research should therefore employ large-scale experimental designs, incorporate longitudinal data, and expand the scope of subject matter to verify the sustainability of virtual laboratory benefits across different educational settings. By addressing these gaps, subsequent studies can further validate and refine the integration of virtual laboratories into physics education, ultimately enhancing both the theoretical discourse and practical application of technology-enhanced learning.

CONCLUSION

This study demonstrates that the integration of virtual laboratories with inquiry-based learning significantly enhances students' achievement in physics by improving conceptual mastery, reducing misconceptions, and fostering higher-order thinking skills. The meta-analytic evidence revealed notable gains in average test scores and a narrowing of achievement gaps, indicating that virtual simulations provide equitable and effective learning opportunities across diverse student groups. Optics and electricity emerged as the most frequently and effectively supported subject areas, though broader application in mechanics, thermodynamics, and electromagnetism remains underutilized. The novelty of this research lies in systematically synthesizing findings across multiple studies, confirming that the synergy between inquiry pedagogy and virtual laboratory technology yields stronger and more sustainable learning outcomes than either approach alone. These findings carry important implications for educators and policymakers by highlighting the potential of virtual laboratories as cost-effective, scalable, and safe alternatives to traditional laboratories, particularly in resource-limited educational settings. Nonetheless, the study is constrained by its reliance on secondary data and limited subject scope, suggesting that future research should employ large-scale, longitudinal, and experimental designs to further validate and expand the evidence base on the pedagogical value of virtual laboratories in physics education.

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