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Exploring Publication Trends, Geographic Contributions, and Research Collaborations in Virtual Labs for Physics Learning: A Systematic Literature Review

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Abstract: This study aims to review and synthesize research trends on the application of virtual laboratories in physics education published between 2015 and 2025. It focuses on identifying dominant themes, research directions, and emerging opportunities in integrating digital technologies into physics learning. A systematic literature review approach was employed by selecting articles from Scopus-indexed journals and conference proceedings. Relevant studies were identified using keywords related to virtual laboratories, physics education, and digital learning. The selected articles were analyzed using bibliometric and thematic analysis to map publication trends, author contributions, and keyword co-occurrence patterns. The results indicate a significant increase in publications on virtual laboratories, particularly during and after the COVID-19 pandemic. Authors from Indonesia emerged as the most prolific contributors in this field. The dominant themes in virtual laboratory research were closely associated with distance learning and digital technology, reflecting the growing reliance on online and hybrid learning environments. Additionally, virtual lab studies were frequently linked to broader educational themes, including e-learning, curriculum development, and STEM education. Despite these developments, the integration of advanced technologies, such as artificial intelligence, remains limited and represents a strong area of potential for future exploration. Virtual laboratories have become an essential component of physics education, supporting flexible and interactive learning environments. However, current research remains largely focused on basic digital integration rather than on intelligent or adaptive systems. Future studies are recommended to explore the incorporation of artificial intelligence and more advanced pedagogical frameworks to enhance the effectiveness and personalization of virtual lab experiences.

Keywords: virtual lab, systematic literature review.

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INTRODUCTION

Innovation in learning aligns with technological advances (Han et al., 2026; Vasiliadou, 2020). The application of virtual laboratories is one such innovation in learning (Hamed & Aljanazrah, 2020; Kavargyris et al., 2026). Virtual laboratories can be used to develop concepts that students will learn and to conduct experiments anytime, anywhere (Wang et al., 2022; Lee, 2026). Research findings indicate that virtual labs positively influence physics learning (Aljuhani et al., 2018). Previous studies show that virtual labs can be used to reduce the number of students who experience misconceptions (Chen et al., 2026; Dehghanzadeh & Moaddab, 2026; Booth et al., 2012; Chan & Lee, 2023; Clancy et al., 2023); understand abstract and difficult-to-visualize physics concepts (Garabet & Miron, 2010; Conica et al., 2023; Zhang & Choate, 2026);

increasing student motivation and engagement in learning (Herga, Èagran & Dinevski, 2016; Aljuhani et al., 2018); training science process skills such as observation, measurement, and data analysis (Thees et al., 2020); improving student learning outcomes and motivation (Sharma et al., 2022); improving understanding of physics concepts; helping students improve their skills in conducting real experiments (Mielke & Berry, 2009; Alneyadi, 2019).

The findings from previous studies were grouped into several major themes based on the dominant educational outcomes reported in the literature (Darby-White et al., 2019). These themes included: (1) conceptual understanding, which covered studies examining the effectiveness of virtual laboratories in improving students' comprehension of physics concepts and reducing misconceptions (Alwan, 2011; McRorie & McKeown, 2017; Soeharto & Csapó, 2021); (2) science process skills, which included studies focusing on experimentation skills (Bilotta et al., 2026; Hsu et al., 2025; Kavargyris et al., 2026), critical thinking (Chen et al., 2026; Dehghanzadeh & Moaddab, 2026; Price & Price, 2019), problem-solving abilities (Fýlýz & Öztel, 2026; Kong & Zhu, 2026), and inquiry-based learning competencies (Lee, 2026); and (3) affective improvement (Kittel, 2026), which encompassed research related to student motivation, engagement, attitudes toward physics learning, self-efficacy (Wang et al., 2022), and learning satisfaction (Kikas et al., 2024).

Virtual labs for physics learning have been conducted extensively (Darby-White et al., 2019; Husnaini & Chen, 2019; O'Dea et al., 2021). However, the existing body of literature raises several unresolved issues that warrant a more systematic and critical review (McRorie & McKeown, 2017; Lehesvuori et al., 2023; Shapiyeva et al., 2025). First, there is inconsistency in reported findings regarding the effectiveness of virtual labs (Mielke & Berry, 2009; Lehesvuori et al., 2023; Shapiyeva et al., 2025). While some studies highlight significant improvements in conceptual understanding and student engagement, others report limited impact, particularly when virtual labs are not supported by appropriate pedagogical strategies (Mishra et al., 2021). This variation suggests that effectiveness is highly context-dependent, yet the specific conditions that determine successful implementation remain unclear (Lehesvuori et al., 2023; Smallwood et al., 2026).

Second, there is an ongoing debate regarding the role of virtual labs in relation to traditional hands-on experiments (Suno & Ohno, 2023; Wang et al., 2022). Some scholars argue that virtual labs can fully substitute physical laboratories due to their flexibility and safety. In contrast, others emphasize that they should function only as complementary tools, especially for developing psychomotor skills (Sweller, 2010). This lack of consensus indicates a gap in understanding how virtual and physical laboratories can be optimally integrated (Clancy et al., 2023; Gezer, 2015; Lehesvuori et al., 2023).

Third, many studies tend to focus on technological features and usability, rather than grounding their implementation in strong instructional design or learning theories. As a result, there is limited clarity on how virtual labs should be pedagogically structured to support deeper learning outcomes. Furthermore, research trends show a concentration on e-learning and distance education contexts, with relatively little attention given to emerging approaches such as adaptive learning environments or the integration of artificial intelligence.

These gaps highlight that, despite the growing volume of research, the field still lacks a coherent synthesis of evidence, theoretical alignment, and a clear direction for future research. Therefore, a systematic literature review is necessary to critically map existing findings,

identify inconsistencies, and provide a more comprehensive understanding of how virtual laboratories can be effectively designed and implemented in physics education (Garabet & Miron, 2010; Iofciu et al., 2011; Kong & Zhu, 2026; Sypsas et al., 2026).

Therefore, a study and mapping of the contribution of virtual labs to physics learning are needed (Gilliam et al., 2024; Gu et al., 2024). A systematic literature review (SLR) is a study designed to review existing literature. SLR research on virtual labs has been conducted by previous researchers, including studies on virtual labs in chemistry learning (Kirchhoff et al., 2024) and a literature review on the use of virtual laboratories in physics learning (Kittel, 2026; Antonietti et al., 2025). The research conducted by Kittel (2026) and Antonietti et al. (2025) reviewed research articles on virtual labs in physics learning published in national journals between 2019 and 2023 and identified using Google Scholar. The difference between this study and previous studies is that it reviews research articles on the application of virtual labs in physics education indexed in Scopus and published from 2015 to 2025 (the last 10 years). However, the contribution of this study is not limited to expanding data coverage across databases and time spans.

This study aims to provide a deeper theoretical contribution by synthesizing existing findings into a more integrative conceptual understanding of how virtual laboratories influence physics learning. Specifically, this study develops a conceptual framework that categorizes the contribution of virtual laboratories into several interrelated dimensions, including conceptual understanding, science process skills, learning motivation, and experimental competence (Gutiérrez-García et al., 2024; Mukagihana et al., 2022). By organizing prior findings within this framework, the study moves beyond a descriptive review to offer a structured interpretation of the mechanisms by which virtual laboratories affect learning outcomes (Chen, 2026; Rodríguez-Molina et al., 2026; Suno & Ohno, 2023). In addition, this study critically examines inconsistencies and variations in previous research findings, such as differences in effectiveness across learning contexts, student characteristics, and instructional designs. This study is expected to provide comprehensive knowledge for teachers and researchers about the contribution of virtual labs in physics education.

Despite the growing body of evidence supporting the effectiveness of virtual laboratories, integrating this technology into physics education is not without its challenges and ongoing debates (Lin et al., 2026; Moher et al., 2009; Shapiyeva et al., 2025). From a theoretical perspective, the use of virtual laboratories can be examined through several learning theories (Kavargyris et al., 2026; Jarutkamolpong & Kwangmuang, 2025; Sypsas et al., 2026). Constructivist theory emphasizes that knowledge is actively constructed by learners through interaction with their environment (Chen et al., 2025; Jarutkamolpong & Kwangmuang, 2025). Virtual laboratories align with this perspective by allowing students to manipulate variables, observe outcomes, and construct their own understanding of physical phenomena (Chen et al., 2025; Garabet & Miron, 2010). In addition, experiential learning theory highlights the importance of learning through experience, which virtual labs attempt to simulate in a digital environment (Adler & Akad, 2024; Chi et al., 1994; Sweller, 2010). However, questions remain regarding whether virtual experiences can fully replicate the depth and authenticity of hands-on physical experimentation (Antonietti et al., 2025; Iofciu et al., 2011).

One key debate in the literature concerns the extent to which virtual laboratories can replace or complement traditional laboratories (Agyare et al., 2025). Some researchers argue that virtual labs offer significant advantages, such as accessibility, cost efficiency, safety, and flexibility (Korthals et al., 2024; Suno & Ohno, 2023).

These features are particularly beneficial in contexts where schools face limitations in laboratory equipment, time, or safety conditions (Saefan et al., 2026). Virtual labs also enable repeated experimentation without additional cost or risk, a capability that is difficult to achieve in conventional settings (Conica et al., 2023; Han et al., 2026; Kirchhoff et al., 2024). Furthermore, the integration of simulations and visualizations allows students to explore abstract concepts such as electromagnetic fields, quantum phenomena, or wave interference that are otherwise difficult to observe directly (Agyare et al., 2025; Rosen & Kelly, 2020; Silitonga et al., 2020).

On the other hand, critics argue that virtual laboratories may lack the tactile and procedural authenticity of real laboratory experiences (Zhang & Choate, 2026). Physical laboratories provide opportunities for students to develop hands-on skills, such as handling equipment, troubleshooting experimental errors, and dealing with real-world uncertainties (Gilliam et al., 2024; Gu et al., 2024; Silitonga et al., 2020). These skills are considered essential components of scientific literacy and cannot be fully replaced by virtual simulations (Lin et al., 2026; Marlina et al., 2023). Therefore, some scholars advocate for a blended or hybrid approach that combines both virtual and physical laboratories to maximize learning outcomes.

In the current state of the art, recent developments in educational technology have significantly enhanced the capabilities of virtual laboratories (Sypsas et al., 2026). Advances in computer graphics, interactive simulations, and artificial intelligence have enabled more realistic and adaptive learning environments (Chan & Lee, 2023; Gilliam et al., 2024; Korthals Altes et al., 2024). Modern virtual labs can provide instant feedback, personalized learning pathways, and data analytics to monitor student performance (Chen, 2026). Moreover, the integration of virtual labs with learning management systems (LMS) and online learning platforms has expanded their role in distance and hybrid learning environments, particularly during and after the COVID-19 pandemic (Akram et al., 2021; Marlina et al., 2025). This shift has accelerated the adoption of digital tools in education and highlighted the importance of flexible and scalable learning solutions (Rodríguez-Molina et al., 2026).

Nevertheless, there is still a need for a comprehensive synthesis of research findings that not only identifies the benefits of virtual laboratories but also critically examines their limitations, research trends, and future directions (Kong & Zhu, 2026; Rodríguez-Molina et al., 2026; Suno & Ohno, 2023). Existing systematic literature reviews tend to focus on specific disciplines, limited time frames, or non-indexed publications. As a result, there is a gap in the literature regarding a broader, more rigorous mapping of research on virtual laboratories in physics education, particularly that indexed in high-quality international databases such as Scopus (Alias & Razak, 2023; Lin et al., 2026).

This study addresses this gap by conducting a systematic literature review of research articles on the application of virtual laboratories in physics education published between 2015 and 2025 and indexed in Scopus. By analyzing trends, research focus areas, methodologies, and key findings, this study aims to provide a more comprehensive and up-to-date understanding of how virtual laboratories contribute to physics learning (Iofciu et al., 2011; Suno & Ohno, 2023; Zhang & Choate, 2026). Furthermore, this study seeks to identify emerging themes and potential research opportunities, including the integration of artificial intelligence, augmented reality, and adaptive learning technologies into virtual laboratory environments.

The significance of this study lies in its potential to inform educators, researchers, and policymakers about the effective use of virtual laboratories in physics education (Fadillah et al., 2026; Shapiyeva et al., 2025). For educators, the findings can serve as a reference for designing

more engaging and effective learning experiences. For researchers, this study provides a foundation for future investigations and highlights areas that require further exploration. For policymakers, the results can inform decision-making on integrating digital technologies into education systems.

Research Questions

Based on the research objectives and bibliometric analysis results, this study is guided by the following research questions:

1. How are publications distributed, and what are the main journal sources that publish articles on virtual laboratories in physics education?
2. What are the patterns of correlation between research themes, publication sources, and the geographical distribution of authors in studies on virtual laboratories in physics education?
3. Which countries contribute the most to publications related to virtual laboratories, and what are the patterns of research collaboration that have been formed (Single Country Publications (SCP) and Multiple Country Publications (MCP)?
4. What is the structure and direction of the development of virtual laboratory research themes in physics education based on thematic map analysis?

METHOD

This study utilized a survey method on the Scopus website. Scopus is considered to be an up-to-date and comprehensive database. This study employed a systematic literature review to address all research questions. All articles collected were accessed through Scopus in October 2025 by typing the keywords "virtual laboratory" OR "virtual lab" OR "online laboratory" OR "simulation". AND ("physics education" OR "physics learning".

Research Design

This study employed a systematic literature review (SLR), combined with bibliometric and thematic analyses, to examine the development of virtual laboratory research in physics education. The design was selected to systematically identify, evaluate, and synthesize existing studies, while also mapping publication trends, research themes, and knowledge structures within the field. This approach enables a comprehensive understanding of both the quantitative patterns and qualitative dimensions of the literature.

Search Strategy

The literature search was conducted using the Scopus database, a comprehensive, up-to-date source of peer-reviewed publications. Data collection was carried out in October 2025 using the keywords: "virtual AND laboratory AND physics AND learning."

The search process involved several stages: (1) initial identification of articles from the Scopus database; (2) screening based on titles and abstracts to ensure relevance; (3) eligibility assessment through full-text review; and (4) final inclusion of articles that met the research criteria. The initial search yielded **467 articles**, which were then filtered through a step-by-step selection process. The overall procedure for selecting articles is illustrated using a flow diagram in Figure 1.

Inclusion and Exclusion Criteria

To ensure the quality and relevance of the selected studies, the following criteria were applied. Inclusion criteria: (1) Articles published between 2015 and 2025; (2) Studies focused on virtual laboratories in physics education; (3) Publications indexed in Scopus (journals and conference proceedings); (4) Articles written in English; and (5) Empirical studies or review papers relevant to the topic. Exclusion criteria: (1) Articles not directly related to physics education; (2) Studies focusing solely on technical system development without educational context; (3) Non-peer-reviewed documents; and (4) Duplicate records.

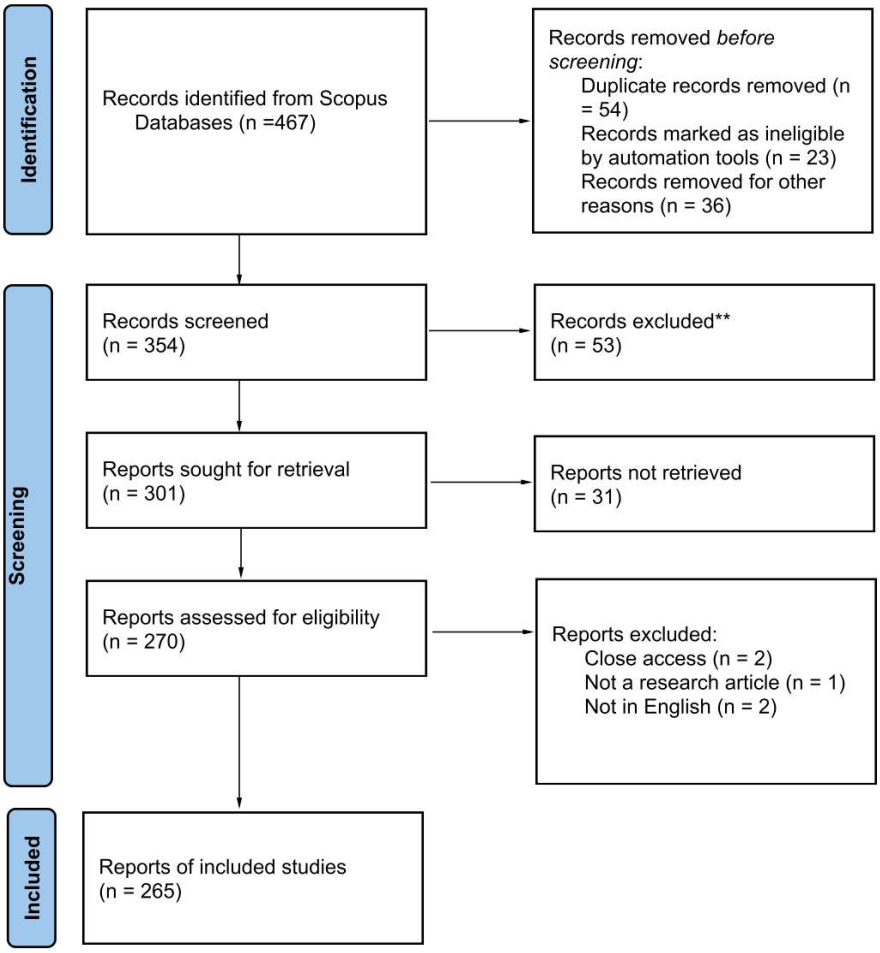

Figure 1. Flowchart for determining the articles' use

These criteria ensured that only relevant and high-quality studies were included in the analysis (Dewi et al., 2020).

Data Analysis

The selected articles were exported in BibTeX format and analyzed using *R Studio* with the Biblioshiny package for bibliometric analysis. The analysis was conducted through several systematic stages (Muhali & Asy'ari, 2026; Alfi et al., 2024). First, bibliographic data were imported and cleaned by removing duplicate records, standardizing author names, and merging similar keywords ("virtual laboratory" and "virtual lab") to ensure data consistency. Second, a descriptive bibliometric analysis was conducted to identify annual publication trends, the most productive authors, influential journals, citation structures, and collaboration networks.

For the keyword co-occurrence analysis, author keywords and keywords plus were extracted and analyzed using a co-word analysis approach. A minimum threshold of five keyword occurrences was applied to reduce noise and retain only the most relevant and recurring terms in the dataset (Napirah & Safiuddin, 2024; Silitonga et al., 2020). The relationships between keywords were normalized using the association strength normalization method to balance the influence of highly frequent and less frequent keywords. Keyword clusters were then generated using the Louvain clustering algorithm, which groups keywords based on the strength of their co-occurrence relationships within the

network (Samsudin, Suhendi & Wulan, 2017). This clustering process enabled the identification of major research themes and thematic relationships in the field of virtual laboratories for physics learning.

Thematic mapping was further conducted by calculating two dimensions: centrality and density (Hidayat & Redjeki, 2020). Centrality was used to measure the importance and connectivity of a theme within the overall research field, whereas density represented the theme's internal development and cohesion. Based on these measures, themes were classified into four categories: motor themes, niche themes, emerging or declining themes, and basic themes.

In addition to bibliometric analysis, thematic analysis was conducted qualitatively to interpret the content of the selected studies. The thematic analysis employed an inductive approach, in which themes were derived directly from the data rather than predetermined theoretical categories (Sulistina et al., 2024; Gunawan et al., 2018). The process began with repeated reading of the selected articles to gain a comprehensive understanding of the research content (Hamdani, 2014; Hamdani, 2022; Saputra, 2022). Subsequently, open coding was conducted to identify key statements, findings, and recurring concepts related to the implementation and impact of virtual laboratories in physics learning.

The identified codes were then compared and grouped into broader categories based on conceptual similarities. Through an iterative coding process, these categories were refined into major themes, such as conceptual understanding, science process skills, and affective improvement. During this stage, each article could be assigned to more than one thematic category, depending on the study's focus and reported outcomes. The coding and categorization process was continuously reviewed to ensure consistency and minimize overlap between themes.

To enhance the validity and reliability of the thematic analysis, the coding process was conducted independently by two researchers. The coding results were then compared and discussed to resolve discrepancies and reach agreement on the final thematic categories (Fadillah et al., 2026; Rizki et al., 2025). Inter-rater reliability was measured using Cohen's Kappa coefficient to assess the level of agreement between coders (Mielke & Berry, 2009). The coefficient obtained indicated substantial agreement, suggesting that the coding process was sufficiently reliable and consistent in identifying themes across the selected studies (Widiyatmoko & Shimizu, 2018). Figure 2 shows Biblioshiny as software for interactive analysis, which includes the collection, analysis, and visualization of scientific literature data.

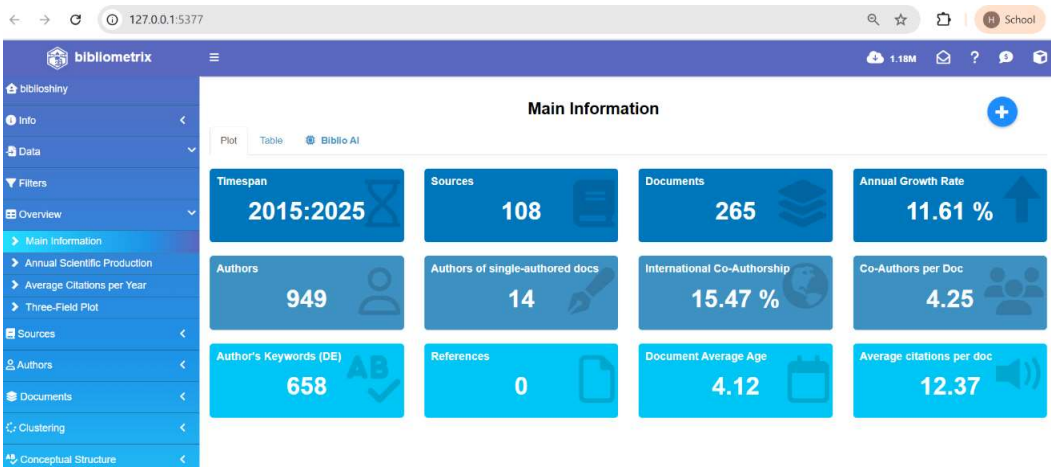

Figure 2. Biblioshiny display

■ RESULT AND DISCUSSION

Publications Distributed and the Main Journal Sources that Publish Articles on Virtual Laboratories in Physics Education

The articles used were published between 2015 and 2025 (the last 10 years). The restriction to **open-access articles** was applied to ensure full-text accessibility for comprehensive analysis, enabling consistent data extraction and evaluation across all selected studies. However, it is acknowledged that this criterion may introduce **selection bias**, as it excludes potentially relevant studies published under subscription-based access. This limitation has been recognized in the study, and future research is recommended to incorporate both open-access and non-open-access articles to provide a more comprehensive and representative overview of the field. There were 265 articles related to virtual laboratories in physics education. All information contained in the reviewed articles was visualized in the form of tables, graphs, diagrams, or other images. The number of articles published increased by 11.6% annually over the last ten years. This upward trend is not merely a statistical pattern but reflects several underlying structural and contextual drivers. One of the primary factors is the rapid advancement of digital technologies, including simulation software, virtual reality, and online learning platforms, which have expanded the feasibility and accessibility of virtual laboratories in physics education.

In addition, educational policy shifts toward digital transformation have played a significant role. Many countries have integrated technology-enhanced learning into national curricula and higher education strategies, encouraging the adoption of virtual laboratories as part of broader efforts to modernize science education. These policy directions have increased both funding opportunities and institutional support for research in this area. A major acceleration in publication growth can also be linked to the COVID-19 pandemic, which forced a sudden transition from face-to-face to remote learning environments. During this period, virtual laboratories emerged as one of the most viable alternatives to physical experiments, prompting a surge in research focused on their implementation, effectiveness, and pedagogical design. This explains the noticeable increase in publications, particularly after 2020.

Furthermore, the growing emphasis on flexible and inclusive learning environments has contributed to the trend. Virtual laboratories are often viewed as cost-effective, scalable, and safe alternatives, especially in contexts where access to physical laboratory infrastructure is limited. This has made them particularly relevant in developing countries, further driving research output. The highest number of articles (41) was published in 2024, indicating an increase in publications on virtual laboratories following the COVID-19 pandemic. Virtual labs can help overcome obstacles to conducting real experiments during the COVID-19 pandemic (Vasiliadou, 2020).

Figure 3 shows the distribution of the most productive publication sources in publishing articles on virtual laboratories in physics education. The analysis was limited to the ten most productive publication sources in this field. Based on the bibliometric results, the *Journal of Physics: Conference Series* published the highest number of articles, with 41 documents, followed by *CEUR Workshop Proceedings* with 14 documents and *AIP Conference Proceedings* with 10 documents. This pattern indicates that conference proceedings outlets dominate the dissemination of research on virtual laboratories in physics education.

The dominance of conference proceedings, particularly the Journal of Physics: Conference Series, suggests several important implications for

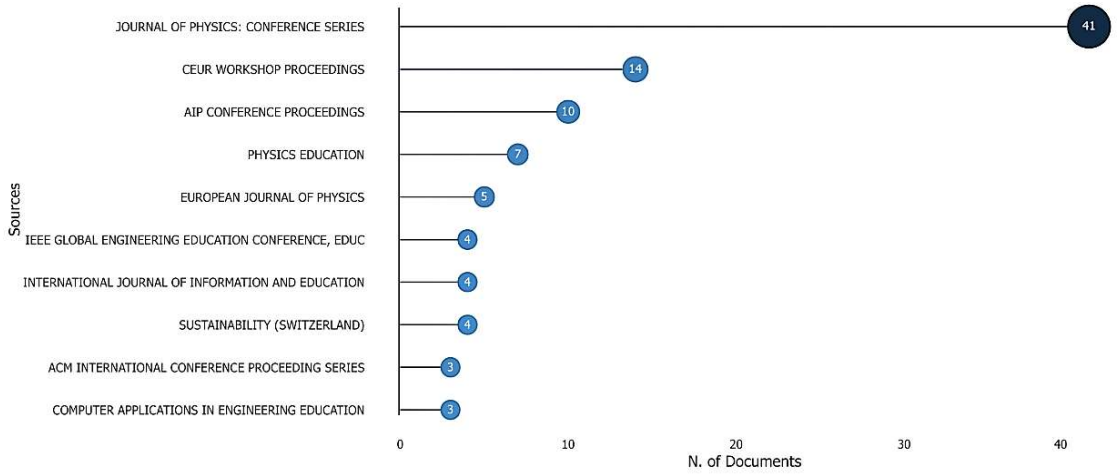

Figure 3. Distribution of the most productive publication sources in publishing articles related to virtual laboratories (virtual labs) in physics education

the development of this research field. On the one hand, conference proceedings provide a rapid platform for researchers to disseminate innovative ideas, preliminary findings, and emerging technological applications in physics education. This condition reflects the dynamic and evolving nature of virtual laboratory research, where technological developments often require fast academic communication and experimentation. The high number of publications in conference-based outlets also indicates strong interest among researchers in exploring digital learning innovations and virtual experimentation environments (Adams et al., 2022).

However, the predominance of conference proceedings may also indicate that the field is still at a relatively exploratory stage and has not yet fully reached methodological maturity. Many conference papers tend to report initial implementations, pilot studies, or small-scale experiments with limited sample sizes and short intervention durations. Compared with articles published in high-impact peer-reviewed journals, conference proceedings generally undergo a less rigorous review process, which may affect the depth of theoretical discussion, methodological robustness, and generalizability of findings. As a result, the current body of literature may still be dominated by descriptive evaluations of virtual laboratory applications rather than comprehensive studies that provide strong empirical evidence regarding long-term learning outcomes, pedagogical effectiveness, or theoretical contributions.

This finding highlights the need for future studies to adopt more robust and rigorous research designs. Future research should emphasize experimental or quasi-experimental approaches with larger and more diverse samples, longitudinal investigations, and stronger theoretical frameworks to better evaluate the effectiveness of virtual laboratories in physics learning. In addition, more studies should be published in reputable peer-reviewed journals to strengthen the scientific credibility and academic maturity of this field. Publishing in high-quality journals would encourage deeper methodological scrutiny, stronger theoretical integration, and broader scholarly impact, thereby advancing virtual laboratory research from an exploratory domain toward a more established, evidence-based area of physics education research.

This condition has important implications for the overall maturity and quality of the research.

Studies published in proceedings often emphasize innovation, implementation, or early-stage evaluation, but may lack deeper theoretical grounding, methodological rigor, or longitudinal validation. As a result, the current body of literature may be characterized by a strong focus on technological experimentation, with comparatively less emphasis on robust pedagogical frameworks and sustained evidence of effectiveness.

Therefore, while the high number of JPCS publications reflects active research engagement and rapid development in the field, it also highlights the need for more rigorous, theory-driven, and peer-reviewed journal studies to strengthen the scientific foundation and ensure the long-term impact of virtual laboratory applications in physics education.

The article by Gunawan et al. (2018), published in JPCS, has the highest number of citations (50). The results of research by Abidin et al. (2020) and Gunawan et al. (2018) indicate that virtual laboratories can improve students' conceptual understanding. Similar results were also found by Arista and Kuswanto (2018); Darby-White et al. (2019); Husnaini and Chen (2019); Udin and Ramli (2020).

There are 14 documents published in CEUR Workshop Proceedings, making it the second-most-published venue. This shows a strong tendency to present research results on virtual labs at international seminars or scientific forums. Meanwhile, AIP Conference Proceedings ranks third with ten documents. This confirms that conference proceedings are a frequently used medium for disseminating innovative research results, especially those involving physics simulations.

The Physics Education journal published 7 articles, and the European Journal of Physics published 5 articles. Both journals have a strong reputation in the field of physics education research (PER) and serve as forums for scientific discussion of learning that applies virtual experiments. The article by Price and Price (2019) was the most-cited in the journal Physics Education (17 citations). According to Price & Price (2019), virtual labs are not a substitute for real experiments, but virtual labs can be integrated into learning. Virtual laboratories can serve as a substitute for real experiments that involve high-risk hazards (Udin & Ramli, 2020).

Meanwhile, the ACM International Conference Proceedings Series and Computer Applications in Engineering Education each have three publications, indicating the contribution of computer science and engineering in the development of interactive simulation-based virtual laboratory software. The dominance of conference publications suggests that research on virtual labs is still in the early stages of technological development and exploration. Hence, researchers tend to publish preliminary results at conferences before proceeding to high-reputation journals.

What are The Patterns of Correlation Between Research Themes, Publication Sources, and The Geographical Distribution of Authors in Studies on Virtual Laboratories in Physics Education

Overall, this publication pattern shows that research on virtual laboratories in physics education is dominated by international conferences and physics education journals. This indicates that the issue of technology integration in physics education is still evolving and remains a focus of global research, especially in the context of post-COVID-19 learning, which demands flexibility and efficiency in virtual laboratories.

Figure 4 shows a Sankey Diagram illustrating the relationships among the main keywords (DE), publication sources (SO), and authors' countries of origin (AU_CO) in research on virtual laboratories in physics education. Based

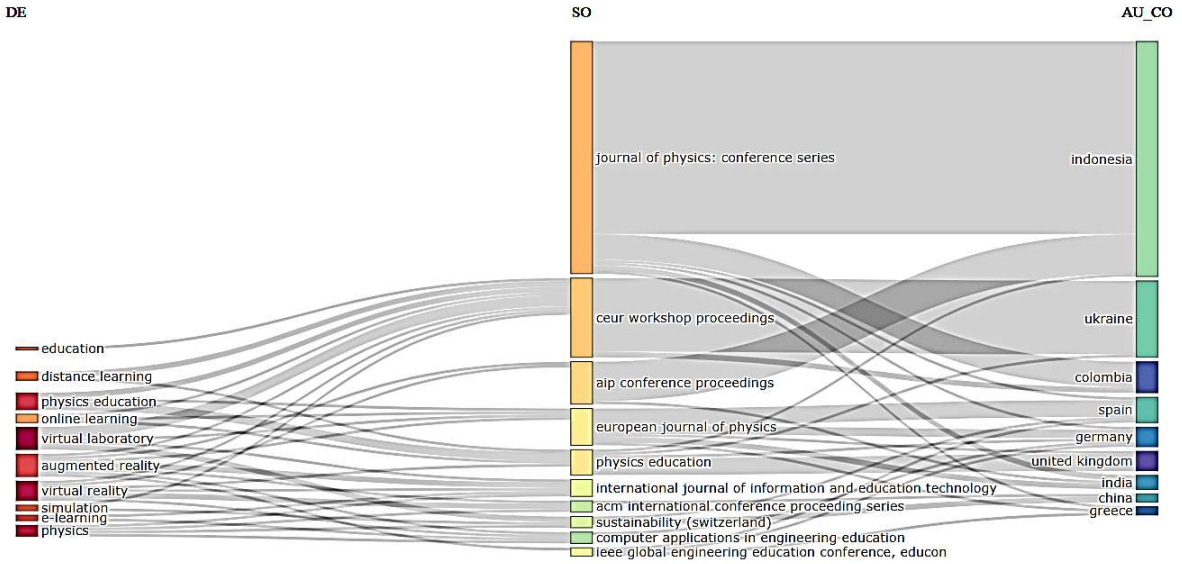

Figure 4. Sankey diagram of the relationship between the main keywords (DE), publication sources (SO), and authors' countries of origin (AU_CO)

on Figure 4, there is a correlation between the research theme, publication location, and geographical distribution of authors.

Education, distance learning, physics education, online learning, and virtual laboratory are keywords (DE) that frequently appear in articles. The integration of distance learning technology with virtual laboratories is a solution to overcome the limitations of real experiments (real experiments), especially after the COVID-19 pandemic. Despite the difficult circumstances during the COVID-19 outbreak, there has been an increase in the use of virtual laboratories to support learning (Kavargyris et al., 2026). In addition, the terms augmented reality, simulation, and virtual reality indicate the development of learning that applies computer-based technology. According to Mishra et al. (2021), augmented reality in virtual labs is a relevant application for use in education and teaching.

The Journal of Physics: Conference Series (JPCS) is the dominant platform for disseminating research results on virtual laboratories, followed by CEUR Workshop Proceedings and AIP Conference Proceedings. This was detected in the publication source (SO) section. These three sources are proceedings that publish papers presented at scientific meetings. Theoretical articles on the development of virtual learning and pedagogical analysis are published in other journals such as Physics Education and the European Journal of Physics.

The geographical dynamics of the research are reflected in the correlation between the authors' countries of origin (AU_CO) and the keywords (DE). Indonesia ranks highest as the contributor of the most articles, especially in JPCS. A total of 26 articles written by Indonesian researchers were published in JPCS. Gunawan is the most prolific contributor, publishing four articles in JPCS. The results of the study show that virtual labs can improve conceptual understanding (Gunawan et al., 2018); increase student creativity (Gunawan et al., 2020); and improve mastery of physics concepts (Dewi et al., 2020). The adoption of digital learning, one of which is virtual laboratories, is a rapidly growing research topic in Indonesia. Other countries that actively contribute include Ukraine, Colombia, Spain, Germany, India, and China. The large

number of countries conducting research indicates that virtual laboratories in physics and science education are being studied globally and across disciplines.

There is a strong relationship between the keywords (DE) virtual laboratory and distance learning, with publications from Indonesia on the optimization of digital simulation-based distance learning, especially during and after the COVID-19 pandemic. E-learning-based virtual laboratories improve the quality of learning and develop students' metacognitive abilities in physics experiment courses (Iofciu et al., 2011).

This shows that Indonesia pays attention to distance learning and virtual labs. During the COVID-19 pandemic, virtual laboratories played an important role in learning physics concepts. Virtual laboratories are one of the media that can be used to conduct concept discovery activities through computer-based simulations (Saparini et al., 2021).

Countries Contribute the Most to Publications Related to Virtual Laboratories and the Patterns of Research Collaboration that Have Been Formed (Single Country Publications (SCP) and Multiple Country Publications (MCP)

Three important criteria in virtual laboratory research have been published in scientific proceedings and journals. These criteria include: (1) the application of distance learning technology; (2) pedagogical innovation using virtual laboratories; and (3) the active contribution of developing countries in adopting and implementing virtual laboratories. These results are consistent with studies by Adler & Akad (2024), which show a significant increase in publications on virtual laboratories.

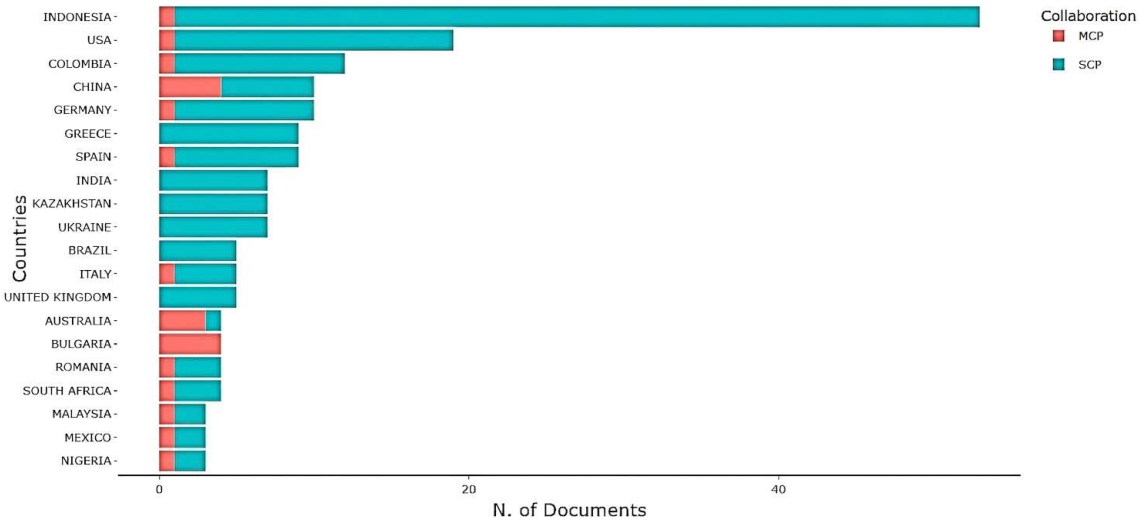

Figure 5. Single country publications (SCP) and multiple country publications (MCP)

The distribution of publications based on the author's country of origin and type of research collaboration, namely Single Country Publications (SCP) and Multiple Country Publications (MCP), is presented in Figure 5. Single Country Publications (SCP) refer to articles written by authors from one country, while Multiple Country Publications (MCP) refer to articles written by authors from two or more different countries.

Indonesia is productive in developing articles on virtual laboratories. There are 53 articles published, with 52 SCP articles and 1 MCP article. This condition reflects Indonesia's productivity at the national level, but minimal

collaboration with researchers outside Indonesia. This pattern reflects Indonesia's high level of research productivity at the national level, yet relatively limited collaboration with international researchers. Several factors may contribute to this condition. First, collaboration networks appear to be dominated by domestic institutions, with many studies conducted within local or national research groups, potentially reducing opportunities for cross-country partnerships. Second, institutional and structural barriers, such as limited access to international funding schemes, differences in research priorities, and administrative constraints, may hinder broader collaboration. Third, language and publication practices may also play a role, as some studies are developed primarily for national dissemination before being adapted for international audiences. In contrast, countries with higher levels of international collaboration, such as those in Europe or North America, often benefit from established research consortia, cross-border funding programs, and strong inter-institutional networks, which facilitate joint publications and knowledge exchange. These systems enable more integrated and sustained collaboration across countries. Therefore, the findings suggest that while Indonesia demonstrates strong research output, strengthening international research networks, institutional partnerships, and collaborative funding opportunities is essential to enhance global engagement and visibility in virtual laboratory research. The dominance of SCP over MCP also occurs in Colombia, the United States, Germany, India, and Ukraine.

Bulgaria ranks first in terms of Multiple Country Publications (MCP). All articles published by authors from Bulgaria involve authors from other countries. China and Australia follow in second and third place. This shows that collaboration between authors from several countries plays an important role in expanding the impact of virtual laboratory implementation in global learning.

Meanwhile, Romania, Malaysia, South Africa, Mexico, and Nigeria have published articles on virtual labs, albeit in relatively small numbers. The involvement of these countries shows that interest in virtual laboratories is spread across the globe. Overall, developing countries such as Indonesia dominate research on virtual laboratories. This dominance illustrates a significant transformation in the orientation of physics education research towards digitalization, while also emphasizing the importance of increasing international collaboration to ensure the resulting research has a global impact.

Figures 4 and 5 illustrate the relationship between research topics, publication sources, and country contributions, as well as the pattern of international research collaboration in studies on virtual laboratories in physics education. The findings show that Indonesia has the highest number of publications among countries, particularly in conference proceedings outlets such as the Journal of Physics: Conference Series. Despite this high productivity, the proportion of international collaboration remains relatively low, as indicated by the dominance of Single Country Publications (SCP) over Multiple Country Publications (MCP).

This pattern can be interpreted from several critical perspectives. First, the high publication productivity of Indonesian researchers may be closely related to national higher education policies that strongly encourage academic publication as a requirement for graduation, academic promotion, and institutional performance evaluation. In recent years, universities in Indonesia have increasingly emphasized publication output indexed in international databases such as Scopus. As a result, conference proceedings have become a popular publication channel because they provide faster publication processes, lower barriers to entry, and broader accessibility for researchers seeking to meet institutional publication targets.

Second, the relatively low level of international collaboration may reflect structural

and institutional challenges within the Indonesian research ecosystem. Limited international research funding, unequal access to global research networks, and language barriers may reduce opportunities for collaboration with researchers from other countries. In addition, many studies on virtual laboratories in physics education are conducted within local educational contexts and are often designed as classroom-based interventions in specific institutions, which may limit the incentive or necessity for cross-country collaboration. The dominance of conference proceedings also suggests that many studies remain exploratory or practice-oriented, focusing on local implementation rather than on large-scale collaborative projects that typically require international partnerships.

Another possible factor is the limited availability of long-term collaborative research grants that specifically support international partnerships in educational technology and physics education research. Compared with researchers in countries with stronger research infrastructures, Indonesian researchers may face difficulties accessing international mobility programs, joint research schemes, or collaborative funding opportunities. Consequently, research activities tend to remain institutionally or nationally concentrated.

These findings suggest several important recommendations for strengthening the global impact and scientific maturity of research on virtual laboratories in physics education. First, universities and research institutions should encourage and facilitate international collaborative research through joint projects, visiting scholar programs, and partnerships with foreign universities. Second, funding agencies should provide more targeted grants for international collaborative research in educational technology and STEM education. Third, researchers should be encouraged to publish not only in conference proceedings but also in reputable international peer-reviewed journals to increase research visibility and scholarly impact.

The Structure and Direction of the Development of Virtual Laboratory Research Themes in Physics Education Based on Thematic Map Analysis

Figure 6 shows a thematic map generated from a bibliometric analysis of publications related to virtual laboratories in physics education. This analysis maps various research themes based on two main parameters:

a. Relevance degree (centrality): indicates the degree of connection between the theme and the field of research in general.
b. Development degree (density): indicates the depth or maturity of the theme's development.

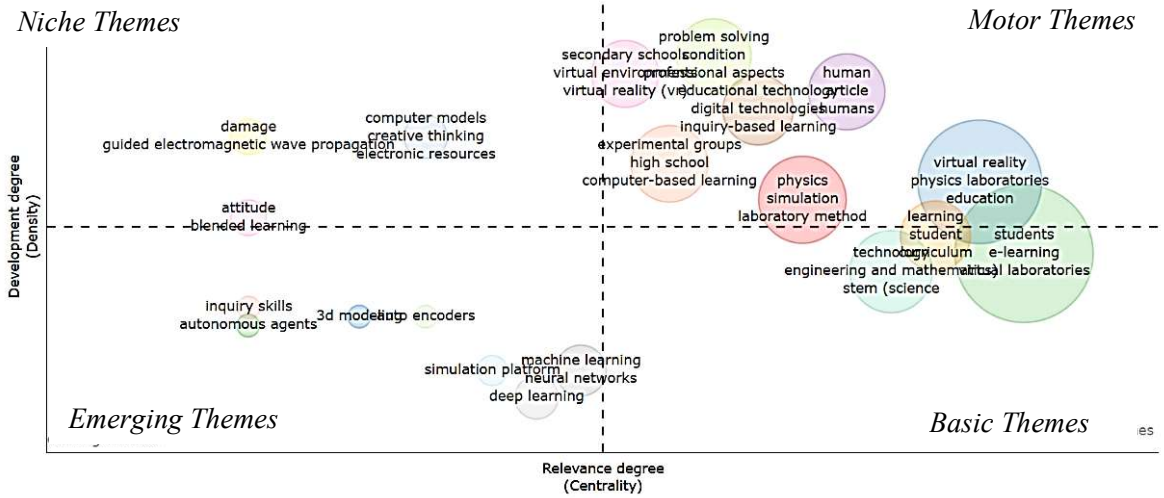

Figure 6. Thematic map of virtual laboratory publications in physics education

Based on Figure 6, the thematic map of virtual laboratory publications in physics education is divided into four quadrants, each representing the conceptual position and level of development of research themes in the field. The upper-right quadrant represents *motor themes*, namely themes characterized by high centrality and high density, indicating that they are both well-developed and strongly connected to other research topics. In this study, "virtual reality" is classified as a motor theme, suggesting that the fundamental application of virtual reality in physics education has become an established and influential area of research. This strong position is reflected in its close relationship with major educational constructs, including virtual laboratories, physics learning, e-learning, and student engagement. Existing studies have extensively explored the use of virtual reality to support conceptual understanding, interactive experimentation, and simulation-based learning experiences in physics education.

However, it is important to distinguish between virtual reality as a foundational technology and its more advanced future-oriented applications. While the core implementation of virtual reality in physics education is mature and well integrated into the research landscape, emerging developments such as metaverse-based learning environments, fully immersive collaborative simulations, and AI-integrated virtual learning ecosystems remain less developed. These advanced applications tend to appear in niche or emerging-theme categories because empirical studies remain limited, theoretical frameworks are fragmented, and large-scale implementation in educational contexts remains relatively uncommon.

Therefore, the apparent contradiction can be resolved by understanding that the thematic map reflects different layers of technological development. The foundational concept of virtual reality has already attained a central, mature position in the field. In contrast, its next-generation applications are still evolving and have not yet gained broad integration within the wider research network. In this context, niche and emerging themes should not be interpreted as weak or unimportant areas, but rather as specialized domains with strong future potential that require further empirical validation and conceptual development.

To support the transition of these emerging applications from niche or emerging themes toward motor themes, future research should address more specific and robust research questions. For example: (1) How does metaverse-based virtual laboratory learning influence students' conceptual understanding and science process skills compared to conventional virtual reality environments? (2) What pedagogical models are most effective for integrating immersive virtual reality and metaverse technologies into physics laboratory instruction? Furthermore, (3) How can collaborative virtual environments improve student interaction, engagement, and problem-solving skills in physics experiments? Addressing these questions through longitudinal studies, cross-institutional collaborations, and rigorous experimental designs may help strengthen the theoretical foundation and empirical evidence of advanced virtual reality applications. As these studies become more integrated and widely cited, such themes may gradually shift from niche or emerging categories into central motor themes within the research landscape of physics education.

Furthermore, the presence of basic themes such as e-learning, students, and curriculum indicates that the field remains strongly anchored in general educational discourse, serving as the conceptual foundation that supports more advanced technological developments. At the same time, emerging themes such as artificial intelligence, machine learning, and simulation technologies suggest a shift toward more adaptive

and intelligent learning environments. However, these themes are still underdeveloped and lack strong integration with mainstream research. The dominant themes in this area are "Virtual reality," "Physics laboratories," "Education," "Students," and "E-learning."

These themes indicate a research focus on implementing virtual reality and physics laboratories in the learning process. This topic also highlights research on student-centered learning approaches that use e-learning. In addition, the relationship between virtual laboratories and students indicates that the research not only explores technological aspects but also tests the effectiveness of virtual laboratories on student learning outcomes, motivation, conceptual understanding, and scientific thinking skills (Aljuhani et al., 2018).

The lower-right quadrant includes themes with high relevance but that are still under development. Themes such as learning, curriculum, STEM, and technology fall into this category. This indicates that research on virtual laboratories is beginning to be integrated into science curriculum development and STEM (Science, Technology, Engineering, and Mathematics) education.

Researchers are testing whether virtual laboratories can support the curriculum, improve conceptual understanding of physics, and connect theory with experiments (Akram et al., 2021). Thus, this area provides a foundation for further research that can combine aspects of instructional design, learning assessment, and the integration of digital technology in the classroom.

Themes such as computer models, creative thinking, and electronic resources are in the upper left quadrant (Niche Themes). These themes are specific and in-depth, but have not been widely researched. Research in this area typically examines innovative approaches to enhancing students' creativity and problem-solving skills through simulation models or specific digital learning resources.

Although their relevance to physics education is not yet high, these themes have the potential to become new areas of research if integrated with Artificial Intelligence (AI), adaptive learning, or metaverse-based applications.

The lower left quadrant shows themes such as machine learning, deep learning, and neural networks. These themes remain of low relevance but have great potential because they relate to automation and personalization in virtual lab-based physics learning. Although still in the exploratory stage, developments in artificial intelligence could drive new directions in research, such as intelligent virtual laboratory systems capable of automatically analyzing student experimental data (Wang et al., 2022).

Overall, this thematic map shows that research on virtual laboratories in physics learning has evolved from the technology-application stage to the pedagogical-integration and digital-innovation stage. The visible directions of development include: increasing learning interactivity through immersive technologies (virtual reality, augmented reality); integration of STEM-based curricula; evaluation of the effectiveness on student learning outcomes; and the potential development of an AI-based smart laboratory system.

In addition to the bibliometric findings presented in Figures 4 and 5, this study further strengthened its analytical novelty by conducting a qualitative content analysis of the 20 most highly cited articles on virtual laboratories in physics education. This additional analysis was important because the bibliometric results revealed two significant patterns: the dominance of conference proceeding publications, particularly in the Journal of Physics: Conference Series, and the high productivity of countries such as Indonesia despite relatively limited international collaboration. These patterns indicate that the field remains largely driven by exploratory, locally oriented studies, underscoring the need to further examine the intellectual and methodological

characteristics of the field's most influential publications.

The 20 most cited articles were selected based on total citation counts in the database. Each article was analyzed qualitatively to identify: (1) the theoretical framework underlying the study, (2) the research design employed, (3) the instruments used for data collection, and (4) the key findings related to learning outcomes and the effectiveness of virtual laboratories in physics education. This analysis aimed to identify whether highly influential studies in the field tend to rely on similar theoretical perspectives, methodological approaches, or evaluation instruments.

The analysis showed that most highly cited studies were grounded in constructivist and inquiry-based learning theories, emphasizing active student engagement and experiential learning processes in virtual laboratory environments. In terms of research design, quasi-experimental approaches were dominant, while relatively few studies employed longitudinal or mixed-methods designs. The most frequently used instruments included conceptual understanding tests, motivation questionnaires, observation sheets, and interviews. The main findings consistently indicated positive effects of virtual laboratories on conceptual understanding, science process skills, motivation to learn, and student engagement. However, the analysis also revealed several important gaps, including the limited use of long-term evaluation designs, small sample sizes, and insufficient exploration of collaborative and immersive learning environments such as metaverse-based virtual laboratories.

■ CONCLUSION

This study provides a comprehensive overview of the development of virtual laboratory research in physics education based on the analysis of 265 articles published between 2015 and 2025. The findings indicate a consistent growth trend in publications, reflecting the increasing relevance of virtual laboratories in supporting digital and flexible learning environments. The dominance of conference proceedings suggests that the field is still in a phase of technological exploration, while journal publications help strengthen pedagogical foundations. The analysis also reveals that research themes are strongly centered on distance learning and digital technology, with virtual reality, e-learning, and physics laboratories emerging as key driving topics. In addition, Indonesia appears as the most productive contributor, although with limited international collaboration. The thematic structure further shows a transition from basic technology adoption toward more integrated and advanced directions, including the incorporation of artificial intelligence. These findings highlight the growing importance of virtual laboratories not only as technological tools but also as integral components in enhancing the quality of physics education and learning.

The implications of this study suggest that virtual laboratories have significant potential to support innovative, accessible, and student-centered learning in physics education, particularly in contexts requiring flexible or remote learning solutions. The identification of dominant and emerging themes provides guidance for educators, researchers, and policymakers in designing more effective and future-oriented instructional strategies, including the integration of intelligent systems and immersive technologies. However, this study also has several limitations. The analysis was limited to articles indexed in the Scopus database, which may not fully represent all relevant research in the field. In addition, reliance on bibliometric and thematic analyses focuses more on publication patterns and keyword relationships than on in-depth evaluation of research quality or learning effectiveness. Furthermore, the limited international collaboration observed, particularly among highly

productive countries, indicates that the global research landscape may not yet be fully interconnected. Future research is therefore encouraged to expand data sources, incorporate more diverse analytical approaches, and explore the pedagogical impact of virtual laboratories in greater depth.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the drafting of this manuscript, the author(s) utilized Google Translate for refining sentence structure/translating text. Following the use of this tool, the author(s) reviewed and revised the content as necessary and accept full responsibility for the final content of the article.

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