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Understanding Virtual Laboratories in Engineering Education: A Systematic Literature Review

Muhamad Nur Azmi Wahyudi [1], Cucuk Wawan Budiyanto [2*], Indah Widiastuti [1], Puspanda Hatta [2], Mohd. Shafie bin Bakar [3]

[1] Vocational Teacher Education Department, [2] Informatics Education Department, Faculty of Teacher Training and Education, Universitas Sebelas Maret, Indonesia, [3] Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia

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***Corresponding Author**
Email address:
cbudiyanto@staff.uns.ac.id

ABSTRACT

Engineering education has gained significant importance in the 21st century due to its integration of essential technological literacy needed in our rapidly changing world. Laboratories, including virtual laboratories, allow students to apply theoretical knowledge practically. Virtual laboratories have emerged as innovative tools that offer increased accessibility and flexibility. This study reviewed 29 peer-reviewed journal articles indexed in Scopus and published between 2018 and 2023 on the use of virtual laboratories in engineering education. The research employed a systematic literature review framework, utilizing PRISMA for article selection. The findings indicate that virtual laboratories provide numerous benefits, including cost-effectiveness, flexibility, safety, and accessibility. They boost student motivation, engagement, and the ability to apply knowledge while effectively enhancing conceptual understanding and practical skills. Virtual laboratories support the development of pedagogical skills and promote careers in engineering by offering a comprehensive and inclusive learning environment. Despite these advantages, challenges like limited interactivity, restricted content, and technical issues persist. Virtual laboratories are valuable supplements to traditional laboratories, providing an economical means to explore phenomena and offering a safe space for experimentation. Educators should consider the benefits and limitations of integrating virtual laboratories into their curriculum. This study aims to deepen the understanding of virtual laboratories in engineering education, advocating for their broader adoption as an innovative tool with a positive impact.

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1. INTRODUCTION

Engineering education has become a crucial area of focus in the twenty-first century, addressing the essential technological literacy needed in today's rapidly evolving world. Economic, demographic, and technological factors present new demands and opportunities (Goldberg, 2014; Nicola et al., 2018). Technological literacy includes understanding and effectively utilizing technology, staying updated on innovations, and integrating these skills professionally (Saltanat et al., 2022). Additionally, it encompasses data literacy, covering technical, legal, and ethical aspects (Giese et al., 2020) and visual literacy for effective communication and problem-solving (Martín Erro et al., 2022). Integrating technology education with historical, social, and ecological contexts is also essential (Abersek et al., 2019). These skills prepare students to navigate and contribute to a technologically advanced society, aligning with engineering education's requirements for teamwork, communication, experimental analysis, process improvement, creativity, and application of experimental results, along with mastering field-specific knowledge, skills, techniques, and tools (Caño et al. et al., 2021). Project-based STEM courses, which enhance teamwork and communication through integrated problem-solving tasks (Lutsenko et al., 2020), automation and robot engineering courses that blend creativity with real-world projects (Hultman & Leijon, 2019), and multi-course project-based learning emphasizing collaborative decision-making and project management (Khandakar et al., 2020), are examples of initiatives that develop these competencies, ensuring students are well-prepared for engineering careers.

Traditional laboratories requiring direct contact with equipment have been widely used to achieve these educational goals. However, they face limitations such as the need for regular maintenance and close supervision (Zhang et al., 2020), struggles to accommodate growing student numbers, lack of 24/7 accessibility, and restrictions on repeated practice and self-paced learning (Bunse et al., 2022; Caño et al. et al., 2021). Additionally, the necessity for physical presence limits inclusivity and poses logistical challenges, especially during crises like the COVID-19 pandemic (Al-Nsour et al., 2022; Salzinger et al., 2023). Virtual laboratories emerged in the early 2000s for computer science and engineering, providing a cost-effective way to simulate experiments. By the 2010s, they expanded across various disciplines, supporting distance learning with remote access to laboratory setups (Reeves & Crippen, 2021). The COVID-19 pandemic accelerated their adoption as institutions sought alternatives to traditional laboratories (Al-Nsour et al., 2022). Today, virtual laboratories use augmented and virtual reality to enhance learning experiences (Sasongko & Widiastuti, 2019). Virtual laboratories are widely used in engineering education, where they play a crucial role in simulating real-world scenarios (Ayas & Altas, 2015; Budai & Kuczmann, 2018; Lu et al., 2015; Yalcin & Vatansever, 2015). A study reported that virtual laboratories had been adopted by over 43,600 users in higher educational institutions over 30 months, driven by early adopters and nodal centers (Achuthan et al., 2020). At The University of Sydney, a virtual reality laboratory saw a 250% increase in student numbers over 2.5 years, with 71.5% of surveyed students reporting enhanced learning outcomes (Marks & Thomas, 2022). In Indonesia, virtual laboratories showed high perceived usefulness and ease of use, enhancing flexibility and productivity in learning (Mursitama et al., 2023).

Virtual laboratories allow students to conduct experiments without actual laboratory equipment, providing a realistic experience without the risks of handling dangerous or expensive materials (Budai & Kuczmann, 2018; Potkonjak et al., 2016; Wolf, 2010). For instance, a virtual fluid mechanics laboratory offered flexibility and individual exercise time without the risks of physical equipment (Zhao et al., 2019), a virtual reality-based chemistry laboratory helped students learn experimental procedures and safety protocols safely (Duan et al., 2020), and virtual X-ray laboratories provided access to advanced equipment simulations, enhancing hands-on practice without high costs (Cherner et al., 2021). Virtual laboratories have several advantages, including improving students' mastery of concepts, problem-solving skills, and scientific thinking, as well as developing their skills in information technology (Hermansyah et al., 2017). These advantages show that virtual laboratories can address the gaps in traditional laboratory settings by providing flexible, repeatable, and safe environments for experimentation, overcoming the limitations of physical laboratories due to resource constraints and safety concerns (Reeves & Crippen, 2021). They allow students to experiment with hazardous or expensive equipment without risks, enhancing problem-solving skills and scientific thinking (Panasiuk et al., 2021). Additionally, by integrating advanced technologies like 3D simulations, virtual laboratories improve IT skills and offer interactive learning experiences (Kumar et al., 2021).

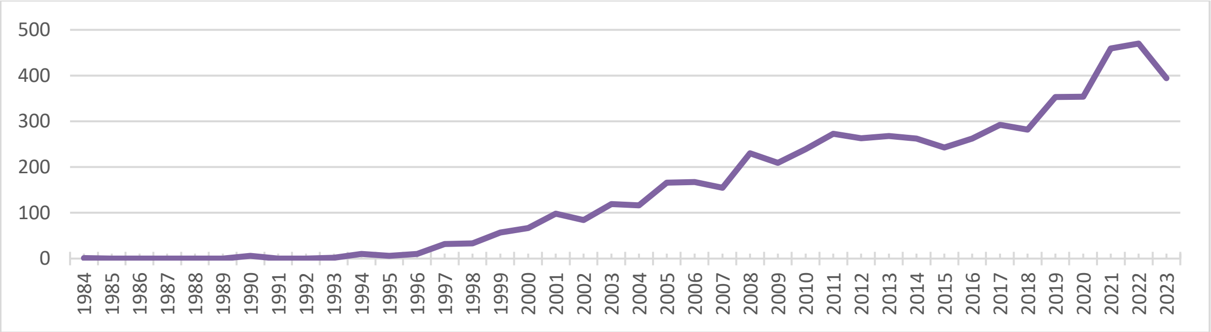

Figure 1. Articles by Year in Scopus with Search Query: TITLE-ABS-KEY ("Virtual laboratory*") PUBYEAR < 2024

Virtual laboratories are gaining popularity, with 5,982 research documents indexed in Scopus from the year of publication of the first article to 2023 (see **Figure 1**). Despite this growth, research in engineering education requires further exploration. A search with the keyword "engineering education" resulted in 1,007 articles, indicating that 16.9% of virtual laboratory research is within the context of engineering education (see **Figure 2**).

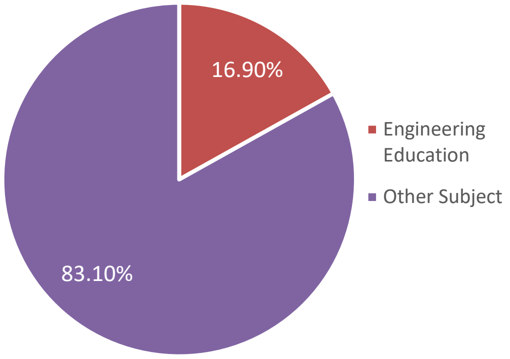

Figure 2. Virtual Laboratory Articles Subject in Scopus

Nolen and Koretsky (2018) investigated the impact of a realistic virtual laboratory on student engagement and interest in the learning process, specifically within engineering practices. Their findings revealed that students experienced heightened engagement, a stronger sense of contribution to group learning, improved opportunities to apply previous coursework, and increased interest in engineering problem-solving through virtual laboratory projects compared to traditional physical labs. Mirauda et al. (2019) introduced an innovative virtual laboratory called "StreamflowVL" for hydraulic engineering students in Italy, simulating a realistic indoor river environment that enhances student engagement, knowledge, and technical skills. Solak et al. (2020) developed a web-based robotics virtual laboratory named "RRC-Laboratory," which allows students to conduct real-time robotics experiments remotely, thereby improving technical knowledge and practical skills without the need for physical lab access. Despite its cost-effectiveness and flexibility, challenges such as ensuring stable internet connectivity, hardware adaptability, and the integration of more optimization techniques and sensors were noted. Research by Caño et al. (2021) explored the benefits and challenges of virtual laboratories, focusing on Chemical and Biochemical Engineering students conducting fermentation simulations. They discovered that virtual labs reduce experiment times and remain accessible during disruptions like the COVID-19 pandemic. However, they identified limitations in the commercial virtual laboratory model related to the learning framework and objectives. Guo et al. (2022) designed a virtual laboratory focused on microgrids with renewable energy sources for learning about solar and wind energy, battery management, microgrids, and power converters. Their results indicated that the virtual lab significantly enhanced students' awareness, interest, and understanding of renewable energy, providing an interactive and convenient platform for experimentation. In 2023, Koretsky et al. conducted a study titled "Connected Epistemic Practices in Laboratory-Based Engineering Design Projects for Large-Course Instruction," which found that virtual laboratory projects offer a greater number and diversity of model components than physical labs. The recent surge in studies underscores the need for updated literature reviews to advance knowledge about virtual laboratories, particularly in engineering education.

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2. MATERIAL AND METHOD

The origin of the first virtual laboratory concept is unclear. Despite this ambiguity, integrating technology in education has led to an understanding that virtual laboratories, as an educational innovation, provide broader opportunities and enhance the learning experience for students in the digital age. An in-depth literature review is essential better to understand virtual laboratories, particularly in engineering education.

Systematic Review Framework

This study follows the systematic literature review framework (Okoli & Schabram, 2010; Robinson & Lowe, 2015) and employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as the method for article selection. Initially published in 2009 and updated in 2020, PRISMA reflects advancements in systematic review methodologies. The PRISMA 2020 statement includes a 27-item checklist and flow diagrams that guide authors in transparently reporting their reviews' rationale, methods, and findings. This update emphasizes clarity, comprehensive reporting, and reproducibility, ensuring systematic reviews are documented thoroughly and accurately (Page et al., 2021). The PRISMA method ensures a rigorous, transparent, and comprehensive data collection and analysis approach. Studies have shown that PRISMA-guided reviews highlight the benefits of virtual laboratories in enhancing students' understanding and skills while identifying gaps and areas for further research (Samala et al., 2023; Sapriati et al., 2023).

Search Strategy

The articles for this research were indexed in the Scopus database and were selected using the following keywords: TITLE-ABS-KEY ("virtual laboratory" AND "engineering education"). Only articles published between 2018 and 2023 were considered, reflecting the period when discussions on the application of virtual laboratories in engineering education became more prevalent.

Inclusion and Exclusion Criteria

Specific criteria were applied to refine the selection process. Only peer-reviewed journal articles presenting clear research questions, methods, and evidence-based interpretations were included. Articles had to be written in English and focused on virtual laboratories in engineering education. Additionally, only accessible articles published between 2018 and 2023 were considered to ensure the relevance of the information and data. A summary of these criteria can be seen in **Table 1**.

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles with clear research questions, methods, and interpretations based on theory and evidence	Non-peer-reviewed articles, conference papers, editorials, book chapters, and articles lacking clear research questions, methods, or interpretations
Language	Articles written in English.	Articles are written in languages other than English.
Focus	Studies focused on the use of virtual laboratories in engineering education.	Studies not focused on virtual laboratories in engineering education.
Access	Accessible.	Not accessible.
Publication Date	Articles published between 2018 and 2023.	Articles published before 2018 or after 2023.

Screening and Selection Process

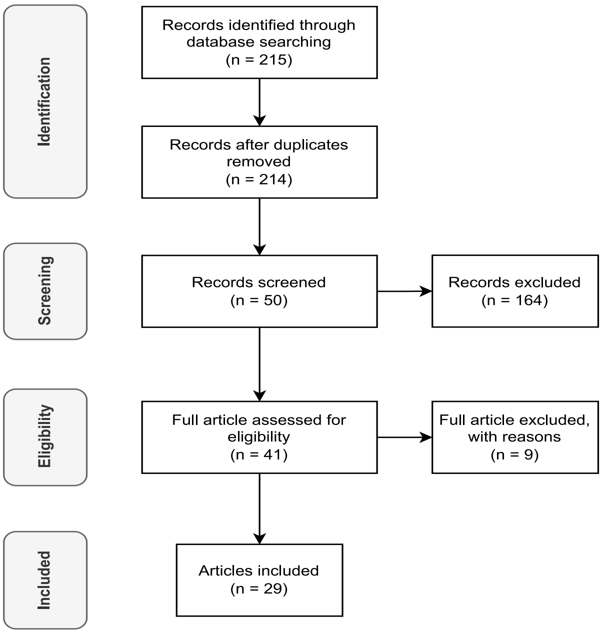

Figure 3. PRISMA Article Selection Process Diagram

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The article selection process, illustrated in **Figure 3**, involved searching the Scopus database using the specified keywords and filters, which resulted in 215 articles. Articles that were not journal articles (such as proceedings, lecture notes, and book chapters), were unrelated to the research theme, not open access, or not in English were excluded. After the screening process, 29 articles were deemed eligible for review.

Data Extraction and Analysis

This study employed an inductive thematic approach to identify the main themes that were found in each of the papers, as described by Braun and Clarke (2006). This procedure is divided into six steps: familiarization, generating, searching themes, reviewing themes, defining and naming themes, and reporting. The familiarization stage was carried out throughout the articles' selection process, as depicted in the PRISMA flow diagram (Fig. 3). This method yielded three major themes: the fundamentals, advantages, and challenges. These three topics will be discussed further in the Discussion section.

3. RESULTS

Research Trends

The following section presents the initial search results, which yielded 215 articles. A bibliometric study using VOSviewer software was conducted to visualize the relationships among keywords, forming clusters that resemble a network (Salmerón-Manzano & Manzano-Agugliaro, 2018) (see **Figure 4**). Each node represents a specific keyword, with larger nodes indicating more related articles. A cluster consists of multiple keyword nodes sharing a common focus. The central cluster, shown in grey, centers on implementing virtual laboratories for education and learning, particularly within engineering education. The blue cluster emphasizes the application of virtual reality, a type of virtual laboratory, especially in online learning. The green cluster is focused on Internet of Things (IoT) learning. The red cluster highlights remote laboratories, an advancement of conventional laboratories that allow students to use real laboratory equipment remotely. The orange cluster is dedicated to power engineering education. The lime-colored cluster, one of the smaller clusters, is focused on learning technology. Finally, the purple cluster concentrates on 3D applications in learning.

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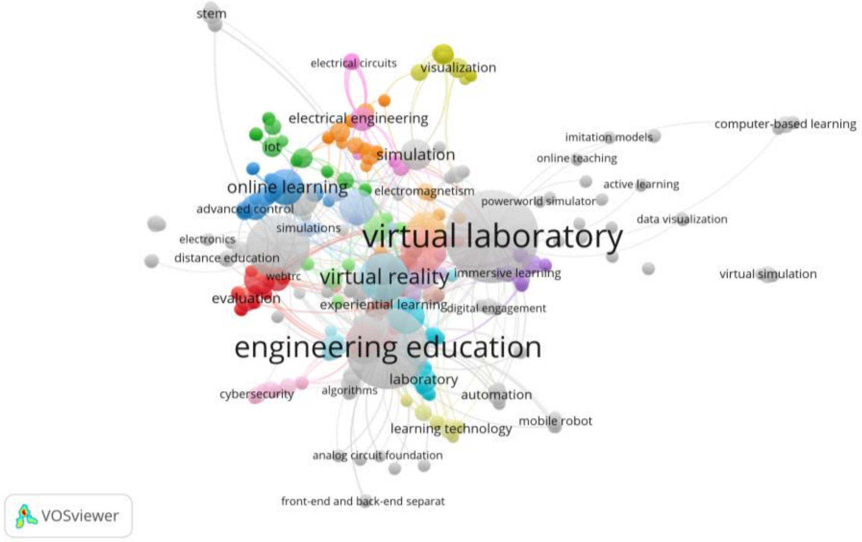

Figure 4. VOSviewer Article Keyword Network

Distribution of Articles by Year

Figure 5 illustrates the distribution trend of each cluster by year. The clusters related to the main themes of this research—virtual laboratories, engineering education, and virtual laboratories clusters—began to show significant activity starting in 2020. This indicates a substantial increase in publications discussing these topics from that year onward. The distribution of eligible articles by publication year, as shown in **Figure 6**, reinforces this observation.

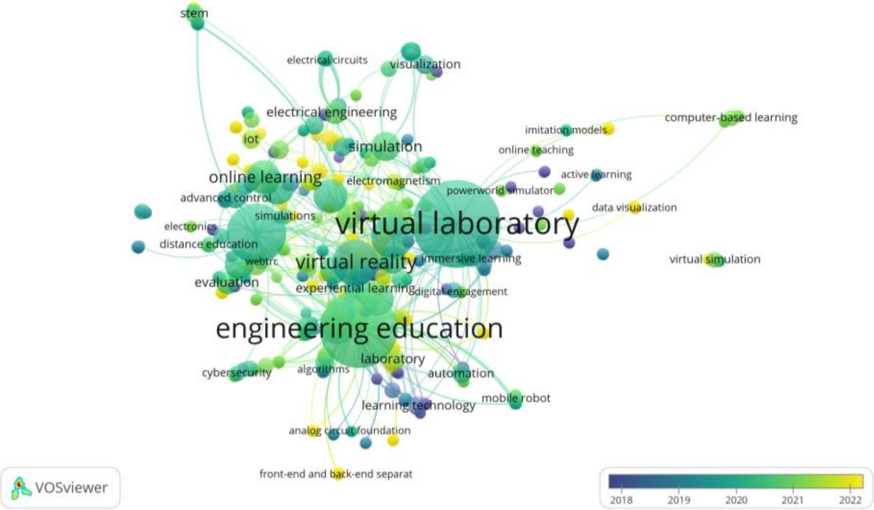

Figure 5. VOSviewer Trend Year Distribution of Each Cluster

Figure 6 reveals that the most eligible articles were published in 2021 and 2022, with nine and six articles, respectively. The year 2020 followed with five articles. In 2018 and 2019, four articles were published each year. There is a noticeable decline in 2023, with only one article published. This data indicates that research on virtual laboratories gained popularity in 2018 and continued to expand until 2023.

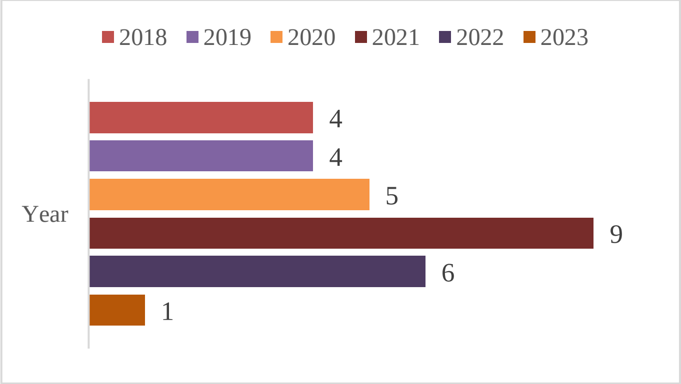

Figure 6. Article Publication Year Distribution

Geographical Distribution

Table 2 presents the affiliation data of authors from 29 articles reviewed for the study, revealing a diverse and global contribution to the field. The United States leads with 12 institutions, indicating a high level of research activity, with notable contributions from the University of Washington and Oregon State University. Turkey follows with four institutions, reflecting substantial interest in this educational technology. China, with five institutions, including Southwest Petroleum University and Wuhan University, also shows significant involvement. This data highlights the widespread academic interest and collaborative efforts across various countries to enhance engineering education through virtual laboratories. Spain, New Zealand, and India, each with multiple institutions contributing to the research, further underscore the global recognition and adoption of virtual laboratories. The presence of universities from diverse regions such as Brazil, Denmark, and Finland also points to broad international engagement in this field. **Figure 7** illustrates the geographical distribution of these institutions, providing a visual representation of the global academic collaboration in this domain.

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Table 2. Geographical Distribution of Institutions

Country	Institutions	Total
United States	University of Washington; Oregon State University; Purdue University; Oklahoma State University; Iowa State University; Northern Illinois University; University of Illinois at Chicago; Boise State University; University of South Carolina; SUNY at Albany; Tufts University; General Motors Global Research & Development	12
China	Southwest Petroleum University; Central China Normal University; Guangdong Medical University; Wuhan University; Southern University of Science and Technology	5
India	Amrita Vishwa Vidyapeetham; Nitte Meenakshi Institute of Technology; SRSMN Government First Grade College; Rajarambapu Institute of Technology	4
Spain	Universidad Internacional de La Rioja; University of Almeria; University of Alcalá; University of Extremadura	4
Turkey	Firat University; Celal Bayar University; Kocaeli University; Kırıkkale University	4
Indonesia	Bina Nusantara University; Universitas Indonesia; Politeknik Penerbangan Indonesia Curug	3
New Zealand	University of Waikato; University of Auckland	2
Australia	School of Technology, Environments and Design, University of Tasmania	1
Brazil	Polytechnic School, Pontifícia Universidade Católica do Paraná-PUCPR	1
Colombia	Universidad Nacional de Colombia, Bogotá	1
Denmark	Technical University of Denmark	1
Finland	University of Eastern Finland	1
Hungary	University of Pannonia	1
Italy	Basilicata University	1
Jordan	Princess Sumaya University for Technology	1
Mexico	Tecnologico de Monterrey	1
Romania	Babes-Bolyai University	1

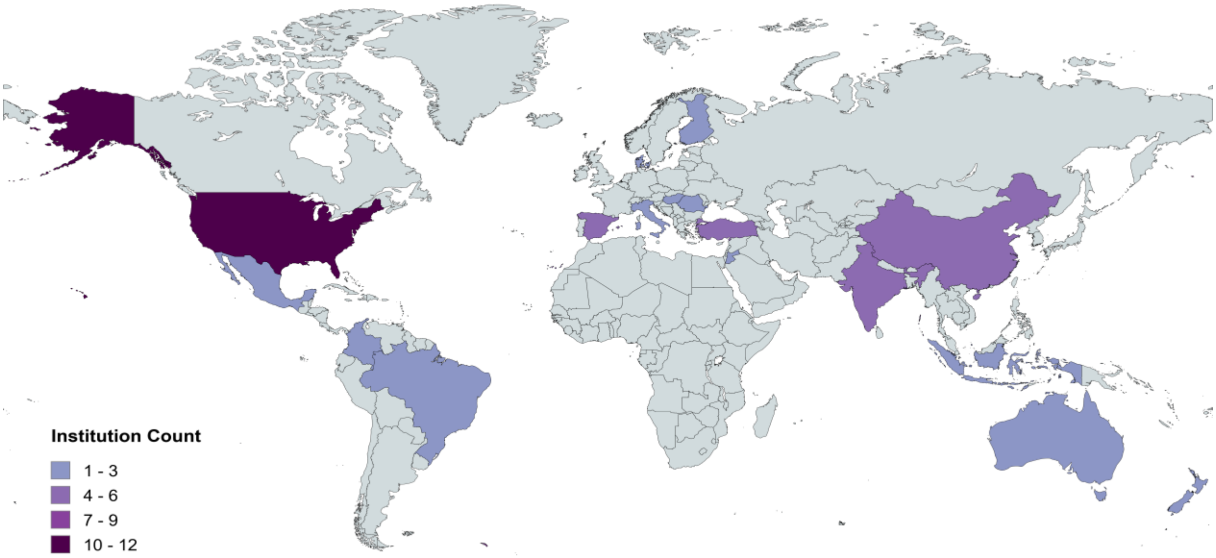

Figure 7. Geographical Distribution Map

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Types of Virtual Laboratories

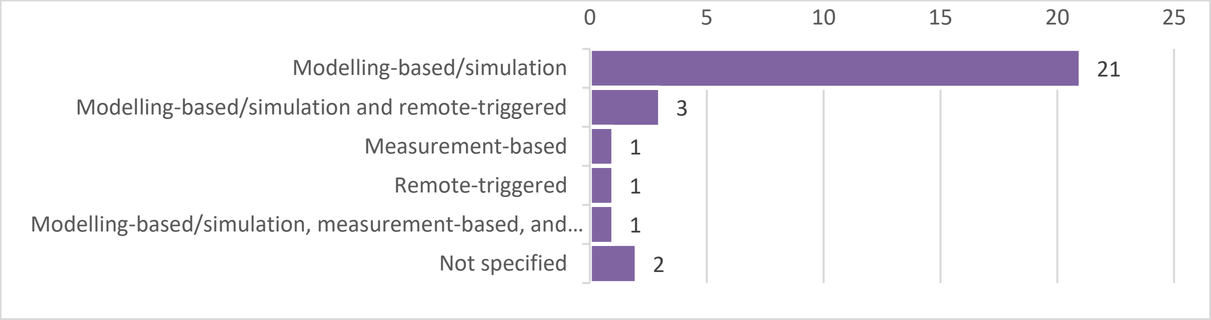

Figure 8. Virtual Laboratory Types

Figure 8 illustrates a notable preference for "modeling-based/simulation" laboratories utilized in 21 articles. Three articles describe laboratories that are "modeling-based/simulation and remote-triggered." Additionally, one article references "measurement-based" laboratories, and another discusses "remote-triggered" laboratories. One article also combines multiple types: "modeling-based/simulation, measurement-based, and remote-triggered." Two articles do not specify the type of virtual laboratory used. This trend emphasizes the prevalence of simulation-based approaches in virtual laboratory implementations within engineering education.

Research Fields Analysis

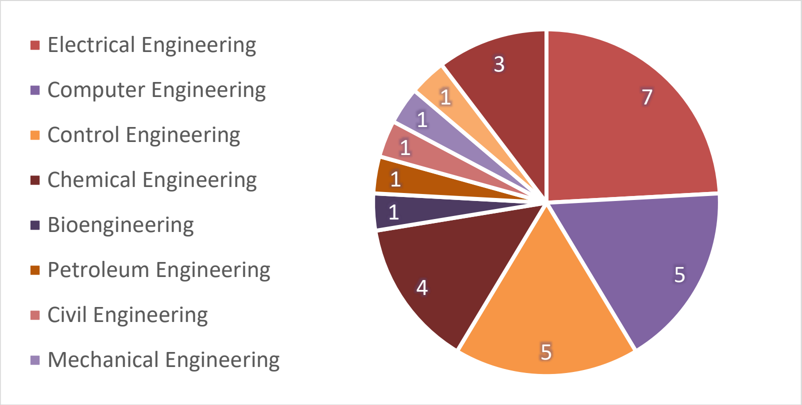

Figure 9. Research Fields Distribution

Figure 9 indicates that virtual laboratories are predominantly used in "electrical engineering," with seven articles dedicated to this discipline. "Computer engineering" and "control engineering" each have five articles, followed by "chemical engineering" with four articles. Other fields, such as "bioengineering," "petroleum engineering," "civil engineering," "mechanical engineering," and "aerospace engineering," are less represented, with one article each. Additionally, three articles do not specify the field. The concentration in electrical and computer engineering highlights the alignment of these fields with virtual laboratory technologies, which facilitate advanced experimental and educational methods.

Citation Analysis

The top ten most cited articles on virtual laboratories in engineering education demonstrate significant influence and diversity in their approaches (see **Figure 10**). Leading the list with 211 citations, one study focuses on modeling-based simulations in computer engineering. Another study, with 95 citations, combines simulations and remote-triggered laboratories in mechanical engineering. Despite not specifying their virtual laboratory types or fields, two articles have garnered 67 and 53 citations, indicating their broad relevance. In bioengineering

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and chemical engineering, two studies using modeling-based simulations have 41 and 40 citations, respectively. Another article with 30 citations integrates simulations and remote-triggered laboratories in control engineering. A focus on chemical engineering is evident in another study with 26 citations. A multidisciplinary approach is employed in one article with 19 citations, while the list is rounded out with 16 citations for a study emphasizing modeling-based simulations in computer engineering. These articles highlight virtual laboratories' diverse applications and significant impact across various engineering disciplines.

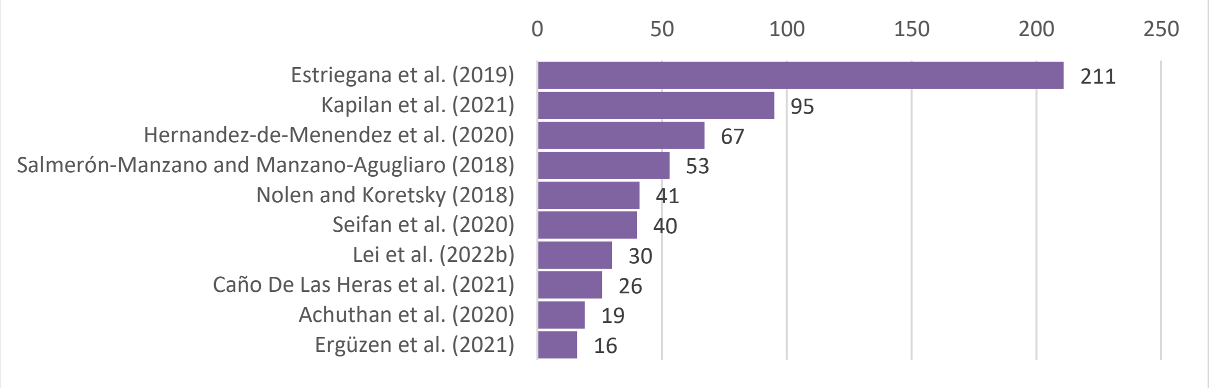

Figure 10. Top 10 Most Cited Articles

4. DISCUSSION

The Fundamental Concept of Effective Virtual Laboratory

Clarifying the definition of a virtual laboratory is essential. There are two general types of laboratories: conventional (physical) and non-conventional, including virtual laboratories. Virtual laboratories emerged due to advancements in Information and Communication Technology (ICT), offering new methodologies to enhance and expand educational opportunities. The development of virtual reality (VR) and 3D simulation technologies has enabled realistic, interactive learning environments that mimic physical laboratory settings, enhancing student engagement and comprehension (Vergara et al., 2022). Cloud-based platforms and open-source software have made virtual laboratories more accessible and cost-effective, facilitating remote experimentation and learning without needing physical presence or expensive equipment (Santamaría-Buitrago et al., 2019). Improved internet connectivity and digital resources, such as animations and simulations, have also supported the deployment of virtual laboratories in geographically remote or economically challenged areas, providing equitable access to high-quality education (Diwakar et al., 2019).

Table 3. Examples of Types of Virtual Laboratories and Their Fields of Application

Article	Virtual Laboratory Type	Field
Zhu *et al.* (2018)**.**	Measurement-based	Petroleum engineering
Mirauda *et al.* (2019)	Modelling-based/simulation	Civil engineering
Solak *et al.* (2020)**.**	Remote-triggered	Control engineering
Kapilan *et al.* (2021)	Modeling-based/simulation and remote-triggered	Mechanical engineering
Purwaningtyas *et al.* (2022)	Modelling-based/simulation	Aerospace engineering

Scholars offer varying perspectives on the definition and types of virtual laboratories. A virtual laboratory is often described as an interactive environment for designing and performing simulated experiments, consisting of simulation programs, data files, and tools that operate on these objects. Students can interact with the virtual laboratory interface, simulate experiments, and adjust parameters to observe new results (Coteli & Gokcan, 2018; Pandey et al., 2022). Examples include a web-based virtual laboratory for a renewable energy microgrid using LabVIEW, Microsoft.Net Core, and Matlab/Simulink (Guo et al., 2022), a mechanical engineering virtual laboratory for fluid mechanics (Kapilan et al., 2021), and a commercial virtual laboratory (Labster) for

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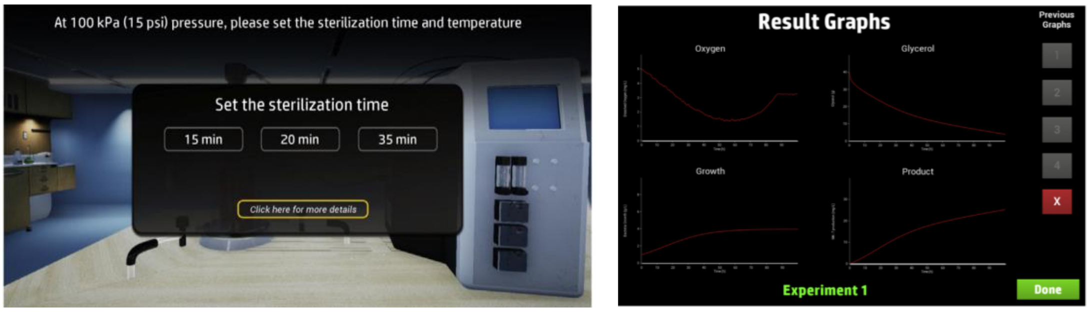
fermentation experiments (Caño et al. et al., 2021). Virtual laboratories can be categorized into three types. The first type, measurement-based laboratories, includes various instrumentation controls that allow students to perform tests and measurement tasks. The second type, remote-triggered laboratories, enables students to use remotely connected real laboratory equipment, though usage must be scheduled due to limited availability. The third type, simulation or modeling-based laboratories, is not restricted to specific locations or times and does not require real laboratory equipment. **Table 3** provides examples of the application of virtual laboratory types in various fields**.**

Virtual laboratories must meet several criteria to achieve learning objectives and become effective and efficient tools in engineering education. A clean and intuitive user interface is essential, along with real-time inputs and outputs and faster simulation times compared to conventional laboratory processes (Szávuly et al., 2019). **Figure 11** illustrates examples of the first three criteria, while **Table 4** details the fourth criterion. Virtual laboratories should also align with existing practices and values, offer advantages over other learning methods, be trialable before use in teaching, be user-friendly for students and teachers, and demonstrate observable results (Achuthan et al., 2020). Additionally, Ramirez et al. (2021) outlined further criteria for an effective virtual laboratory in engineering education. These include cross-platform portability, modularity, compatibility with both software and hardware, standalone application capability, debugging features, extendable libraries, high performance, and a graphical user interface.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(a) (b)

Figure 11. Virtual Laboratory Criteria: (a) User Interface and Inputs, (b) Outputs. Adapted from Seifan *et al.* (2020).

Table 4. Example of Experiment Time Comparison. Adapted from Szávuly *et al.* (2019).

Laboratory Types	Relative Time of Experiment
Physical Laboratory	1
Interpreted Simulation (MATLAB)	0,8
Compiled Simulation (Virtual Laboratory)	0,016

Exploring The Advantages of Virtual Laboratories in Engineering Education

Implementing virtual laboratories in engineering education significantly impacts students' learning experience (Kapilan et al., 2021). Virtual laboratories are an effective resource for conventional face-to-face and remote learning settings (Luse et al., 2021). Compared to conventional laboratory projects, reports from students on virtual laboratory projects show higher levels of motivation, engagement, and perceived contributions to their group's learning, as well as better opportunities to apply prior coursework knowledge (Caño et al. et al., 2021). Virtual laboratory projects also offer greater opportunities for engineering teams to engage in practical work than conventional laboratory projects (Koretsky et al., 2023). Students also demonstrate enhanced time management skills and a better understanding of laboratory procedures than traditional laboratory classes (Kagami et al., 2020). Most students perceive virtual laboratories as necessary for enhancing their comprehension of course material, as these laboratories facilitate a deeper understanding of course concepts. Teachers also benefit from implementing virtual laboratories, as they facilitate the learning process and improve pedagogical abilities (Kapilan et al., 2021). Virtual laboratories are seen as a novel approach to creating a secure,

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enjoyable, and engaging atmosphere for engineering education to improve students' understanding of various subjects (Seifan et al., 2020).

The Integrating virtual laboratories into educational activities optimizes skill acquisition by exposing students to scenarios that may not be feasible with available resources. Additionally, virtual laboratories enhance students' perception and interpretation of real-world phenomena (Salmerón-Manzano & Manzano-Agugliaro, 2018). Research indicates that virtual laboratory projects positively affect end-of-course interest in engineering problem-solving and task-effort orientation. A stronger positive correlation was observed between the inclination to solve engineering problems and the desire to pursue a career in engineering following virtual laboratory courses. This suggests that projects situated in an industrial context may help students link interesting problems with the prospect of an engineering profession (Nolen & Koretsky, 2018). Virtual laboratories in engineering curricula have also been found to augment students' comprehension of theoretical concepts and practical skills (Du et al., 2022; Guo et al., 2022; Mirauda et al., 2019; Zhu et al., 2018), including improving emergency response ability (Zhu et al., 2018). Students recognize the importance of acquiring specific technical skills (Guo et al., 2022; Mirauda et al., 2019) and employ iterative strategies within the virtual environment, facilitating knowledge construction (Guo et al., 2022). The implementation of virtual laboratories positively influences students' academic performance (Ergüzen et al., 2021; Luse & Rursch, 2021) and enhances learning outcomes (Lei et al., 2022; Purwaningtyas et al., 2022). Notable improvements in mean marks across all cases are observed following the implementation of virtual laboratory exercises (Tejado et al., 2021). Virtual laboratories also provide a secure environment for conducting experiments (Luse et al., 2021) and are effective tools for facilitating the comprehension of engineering concepts (Mohamed et al., 2021).

Virtual laboratories represent an innovative approach that promotes resilience, inclusivity, and sustainability by addressing common limitations in laboratory skill training. Various studies indicate that virtual laboratories significantly reduce both time and cost compared to conventional methods (Lei et al., 2022a; Pandey et al., 2022; Yang et al., 2019; Zhu et al., 2018). One notable benefit is the ability for students to conduct experiments using only a personal computer and an internet connection (Solak et al., 2020). This accessibility allows students to perform experiments from any location, including their homes (Pandey et al., 2022), enhancing the effectiveness of distance learning by increasing flexibility and accessibility (Estriegana et al., 2019). Integrating computer technology in virtual laboratory experiments allows students to explore phenomena that are not easily perceptible in traditional settings. For instance, combining augmented reality (AR) with virtual laboratories in aviation engineering education improves problem-solving abilities and personalizes learning (Purwaningtyas et al., 2022). MATLAB has been used to develop virtual laboratories in electrical and chemical engineering education (Coteli & Gokcan, 2018; Szávuly et al., 2019; Guo et al., 2022). A single-board computer was also used to control a robot in a web-based remote-triggered laboratory remotely (Solak et al., 2020).

These methods enable cost-effective, affordable, and timely experiments. Virtual laboratories enhance the quality of courses by expanding the variety of experiments and bringing industrial challenges into the academic realm (Kagami et al., 2020). They also reduce cognitive load by mitigating constraints such as time limitations and the need for technical and operational engagement in traditional laboratory settings (Caño et al. et al., 2021). Virtual laboratories address the technology gap and high equipment costs associated with conventional laboratories (Ramirez et al., 2021). Aligning virtual laboratories with course learning objectives through a backward design approach ensures they support desired outcomes and integrate into assessments (Papaconstantinou et al., 2021). Blended learning approaches that combine virtual and traditional methods improve understanding and provide flexibility (Schnieder et al., 2022). They also facilitate collaborative learning through remote teamwork and real-time feedback (Jara et al., 2012). Integrating virtual laboratories with Learning Management Systems such as Moodle ensures seamless access and structured management of laboratory activities (Al-Khanjari & Al-Roshdi, 2015). Virtual laboratories are widely regarded as advantageous due to their compatibility, simplicity, observability, trialability, and accessibility through various communication channels (Achuthan et al., 2020).

Challenges of Virtual Laboratories Implementation in Engineering Education

Regarding the challenges of virtual laboratory implementation, it is important to note that certain laboratory procedures cannot be replicated through computer simulations and that virtual laboratories may not provide all the necessary skills required for real-world job skills. (Salmerón-Manzano & Manzano-Agugliaro, 2018). Similarly, Caño *et al.* (2021) Virtual laboratories lack the competencies students typically acquire in a conventional laboratory setting, including sensory awareness based on knowledge, psychomotor skills, team experience, and ethical considerations. Certain students contended that the absence of sensory engagement could result in forgetfulness, whereas others expressed dissatisfaction with the closed interactions within the simulated laboratory. Insufficient real evidence may lead students to behave carelessly and operate without a genuine understanding of the principles underlying experimentation. The extent of active experimentation that the students could engage in was restricted. In order to address this challenge, several studies propose that a strategic approach should guide the implementation of virtual laboratories into engineering education. A backward design process aligns virtual laboratory experiences and course learning objectives. Moreover, emphasizing assessments that directly correlate with virtual laboratory outcomes is crucial. (Papaconstantinou *et al.*, 2021). Additionally, Schnieder *et al.* (2022) Advocate for blended learning, which integrates virtual and traditional methods to enhance understanding and flexibility.

Another challenge that virtual laboratory technology must address is the lack of real interaction with equipment, preventing students from experiencing a physical sense of the equipment and impeding their ability to develop their skills. (Hernandez-de-Menendez *et al.*, 2020). This challenge is more pronounced in the case of modeling-based laboratories or simulations that are completely detached from physical equipment. However, measurement-based and remote-triggered virtual laboratories that still require operational equipment provide students with a tangible sense of the equipment. For instance, Zhu *et al.* (2018) Developed a measurement-based virtual laboratory for petroleum and offshore gas engineering education. Meanwhile, examples of remote-triggered laboratories can be seen in the research by Solak *et al.* (2020), who developed a virtual robotics laboratory using real remotely controlled robots. Moreover, the research by Purwaningtyas *et al.* (2022) Explores the utilization of augmented reality (AR) technology in virtual radar laboratories within aviation engineering education. The application of AR aims to enhance interaction during laboratory activities, thereby improving students' problem-solving abilities.

Experimental data in virtual laboratories may be idealized but not accurately reflect real-world conditions (Hernandez-de-Menendez et al., 2020). Integrating real-world data can enhance realism in experimental data (Damiani et al., 2021; Kimko & Lee, 2017). Additionally, students might not always receive adequate guidance or supervision from teachers. The efficacy of imparting health and safety practices to students may be limited, potentially posing challenges for individuals pursuing future academic pursuits that necessitate laboratory work (Hernandez-de-Menendez et al., 2020). Virtual laboratory developers can take inspiration from models that include safety instructions. For example, a virtual fermentation laboratory includes information about potential hazards, requiring students to use laboratory coats, safety goggles, and gloves and wash their hands after experiments, as shown in **Figure 12**.

(a) (b)

Figure 12. Laboratory Formality in Virtual Laboratory. Adapted from Seifan *et al.* (2020).

Yang et al. (2019) noted that many virtual laboratories provide only a general overview of the experimental process, lacking detailed in-process operations and training. Consequently, educators may struggle to monitor and evaluate each experiment phase effectively. Students' learning abilities are impacted by their understanding of virtual laboratory practices and the absence of immediate instructor feedback. This view aligns with Du et al. (2022), who argue that the lack of in-person interaction and unfamiliarity with equipment operation limits students' ability to engage in collaborative work. Providing detailed instructions and involving instructors

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and peers during experiments can mitigate these issues, as demonstrated in virtual laboratories developed by various researchers (Caño et al. et al., 2021; Coteli & Gokcan, 2018; Mirauda et al., 2019; Ramirez et al., 2021; Seifan et al., 2020; Tejado et al., 2021; Yang et al., 2019; Zhu et al., 2018). Gutiérrez et al. (2021) identified several constraints associated with virtual laboratories, including the high cost of initial hardware and software, a steep learning curve for students unfamiliar with the technology, compatibility issues between hardware and software, communication complexity between students and virtual laboratories, capacity limitations, and restricted experiment sampling time.

5. CONCLUSION

Virtual laboratories are increasingly replacing conventional laboratories in various disciplines, including engineering education, which prepares students for real-world situations. To be effective, virtual laboratories must meet specific criteria, such as having an easy-to-use interface, generating real-time input and output data, and compatibility with pre-existing practices. Virtual laboratories have proven to be effective learning tools for both traditional and distance learning, as evidenced by increased student motivation, engagement, and the ability to apply acquired knowledge. Additionally, they enhance students' understanding of subject concepts, assist in developing pedagogical skills, and encourage careers in engineering. Virtual laboratories improve students' grasp of theoretical concepts and practical skills while positively impacting academic performance. They provide a safe environment for experimentation, increase robustness and inclusiveness, and reduce time and costs compared to conventional laboratories. Furthermore, they enhance flexibility and accessibility in distance learning, allowing students to explore phenomena that cannot be seen in person more economically. Several challenges arise with the use of virtual laboratories. They may not provide sufficient skills for real-world applications due to the lack of interaction with physical equipment and deficiencies in developing certain competencies, such as sensory awareness and ethical considerations. Additional obstacles include high costs, steep learning curves, compatibility issues, and capacity limitations. Virtual laboratories cannot fully replace hands-on experience, and there is a risk that students may become less cautious due to the absence of visible physical evidence. Virtual laboratories offer significant benefits, including increased motivation, engagement, and application of knowledge. They create a safe environment for experimentation, reduce costs, and enhance flexibility. Nevertheless, addressing deficiencies in competencies due to limited physical interaction remains crucial. Future research should focus on enhancing realism, bridging the gap between virtual and physical skills, addressing ethical considerations, exploring effective teaching methods, and finding cost-effective solutions. Advancing research in these areas will optimize the use of virtual laboratories and ensure students are well-prepared for real-world challenges.

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