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iJOE International Journal of Online and Biomedical Engineering

iJOE | eISSN: 2626-8493 | Vol. 22 No. 9 (2026) | OPEN ACCESS

https://doi.org/10.3991/ijoe.v22i09.61207

PAPER

A Systematic Literature Review of Virtual Laboratories in Electrical Engineering Education

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ABSTRACT

The application of virtual laboratories in electrical engineering education has increased, spanning various topics, types of virtual laboratories, evaluation methods, learning outcomes, and implementation challenges. This study aims to conduct a systematic literature review based on PRISMA 2020 to provide new insights based on research findings published between 2021 and 2025 from the Scopus and IEEE Xplore databases, focusing on virtual laboratories in electrical engineering education. A total of 20 relevant research studies were selected for analysis. The results show that virtual laboratories are implemented in courses on basic electrical engineering topics and remain predominantly simulation-based environments. The evaluation approach used is predominantly quantitative and perception-based, with an emphasis on cognitive domains and student engagement. Challenges that often arise include instructional design, technical infrastructure, and skill development. Overall, the research findings indicate that virtual laboratories in electrical engineering education are effective as complementary learning environments rather than substitutes for physical laboratories, highlighting the need for future research that is better aligned and more pedagogically rigorous.

KEYWORDS

virtual laboratories, electrical engineering, learning outcomes, educational technology, engineering pedagogy

1 INTRODUCTION

Laboratory-based learning is an important part of electrical engineering education, providing students with the opportunity to translate theoretical understanding into practical understanding through experimental activities, system analysis, and problem-solving. Laboratory practicums play an important role in developing the knowledge, skills, and professional competencies required by engineering graduates [1], [2]. However, the learning process in physical laboratories faces obstacles

Effendi, H., Oktageri, D., Husin, M., Fadillah, M. A., Yunusa, A. A., Nufus, P. Z. (2026). A Systematic Literature Review of Virtual Laboratories in Electrical Engineering Education. *International Journal of Online and Biomedical Engineering (iJOE)*, 22(9), pp. 4–17. https://doi.org/10.3991/ijoe.v22i09.61207

Article submitted 2026-02-21. Revision uploaded 2026-04-28. Final acceptance 2026-04-28.

related to high equipment and maintenance costs, safety issues, limited access to physical space, schedule rigidity, and an increasing number of students, especially in engineering education programs with intensive curricula in laboratory learning [3], [4].

The rapid development of digital technology is increasingly expanding the scope of application of virtual laboratories. Beyond conventional simulation-based platforms, research findings over the last half-decade indicate that integrating immersive virtual reality, augmented reality, digital twins, cloud computing, and Internet of Things technologies can increase realism, interactivity, and scalability [5], [6], [7]. Immersive and extended reality environments have been shown to increase students' sense of presence and engagement, although their long-term effects on learning outcomes and skill acquisition remain inconclusive [8], [9]. Simultaneously, intelligent systems that combine artificial intelligence and large-language-model-based guidance can provide structured learning guidance and support autonomous learning in the context of virtual laboratories [10], [11].

Despite technological advancements in virtual laboratories, their pedagogical effectiveness in electrical engineering education remains debated. Meta-analytic research findings confirm that virtual laboratories exert the strongest influence on students' affective domains, such as motivation and engagement. In contrast, their impact on psychomotor domains and practical skills remains relatively under-identified [12], [13]. Several studies highlight ongoing concerns regarding the absence of tactile interaction, manual manipulation, and authentic equipment operation, which are essential for the development of professional skills in engineering disciplines [7], [14]. Consequently, some researchers recommend hybrid or blended laboratory models that integrate virtual, remote, and physical laboratories to balance accessibility in experiential learning [5], [15].

In addition to pedagogical issues, previous research has shown a marked methodological disparity. The results show a wide range of topics discussed in electrical engineering, the types of virtual laboratories used, and the evaluation approaches employed. Assessment is dominated by self-report questionnaires that assess student perceptions, technology acceptance, motivation, and engagement, while performance-based assessment, observation, and skills-oriented evaluation are underrepresented [16], [17], [18]. Furthermore, reported learning outcomes are often limited to the cognitive domain, with few studies systematically identifying learning outcomes in the psychomotor and affective domains beyond motivation and anxiety [13], [19].

Although several review and bibliometric studies have discussed virtual laboratories in engineering, vocational education, and STEM broadly [9], [20], [21], comprehensive systematic reviews specifically focused on electrical engineering education are still limited. The findings tend to focus more on the feasibility of technology, collaboration, and trends in virtual laboratories across disciplines, rather than on the integrated synthesis of topics, laboratory types, evaluation methods, learning outcome reports, and implementation challenges in the context of learning in electrical engineering education. The increasing use of virtual laboratories as a follow-up to digital transformation, Industry 4.0 demands, and sustainability considerations requires a discussion that specifically focuses on identifying current research trends and confirming gaps for further investigation [15], [22].

To address this gap, this study conducted a systematic review of the literature on the implementation of virtual laboratories in electrical engineering education.

This review systematically maps studies by examining the electrical engineering topics covered, the types of virtual laboratories used, the evaluation methods employed, the categories of student learning outcomes reported, and the main challenges associated with implementing virtual laboratories in the learning process in electrical engineering education. Therefore, this systematic review is guided by the following research questions:

RQ1: What electrical engineering topics are addressed using virtual laboratories?
RQ2: What types of virtual laboratories are used in electrical engineering learning?
RQ3: What evaluation methods are employed in studies on virtual laboratory use in electrical engineering education?
RQ4: What categories of student learning outcomes are reported in electrical engineering learning supported by virtual laboratories?
RQ5: What are the key challenges associated with implementing virtual laboratories in electrical engineering learning?

By synthesizing evidence from relevant research, this review provides a comprehensive and structured overview of research on virtual laboratories in electrical engineering education, offering insights to support pedagogical design, institutional decision-making, and future research directions.

2 METHOD

This study conducted a systematic literature review following the PRISMA 2020 guidelines to ensure methodological rigor and transparency in analyzing research on virtual laboratories in electrical engineering education. A search for relevant articles was conducted using the Scopus and IEEE Xplore databases. The Scopus database search was conducted using the keywords "virtual laboratory" OR "virtual laboratory" and "electrical engineering" OR "electricity" based on Title–Abstract–Keyword, where 325 records were successfully identified. In parallel, IEEE Xplore searches using equivalent keywords in the Title–Abstract fields retrieved 289 records. Overall, the search process identified 614 records. Automated filtering tools then restricted the results to publications from 2021 to 2025 and to journal articles and conference papers, eliminating 472 records and retaining 142 studies. After that, 19 records were removed due to duplicate indications during the duplicate-removal phase, leaving 123 unique studies for screening.

Abstract screening evaluated relevance to virtual laboratory applications in electrical engineering and excluded 47 studies that did not meet the predefined scope. Of the remaining 76 studies, 41 full-text reports were not retrievable and excluded from the screening process. Full-text assessment of the remaining 35 studies applied predefined inclusion and exclusion criteria, as illustrated in Table 1, requiring explicit alignment with electrical engineering education, integration of virtual laboratories into the learning process, and reporting of educational evaluation outcomes such as learning performance, skill development, or learner perceptions. In the full-text assessment stage, 15 studies were excluded for not meeting the established inclusion criteria, leaving 20 included in the review. The overall study selection process is shown in the PRISMA flowchart illustrated in Figure 1.

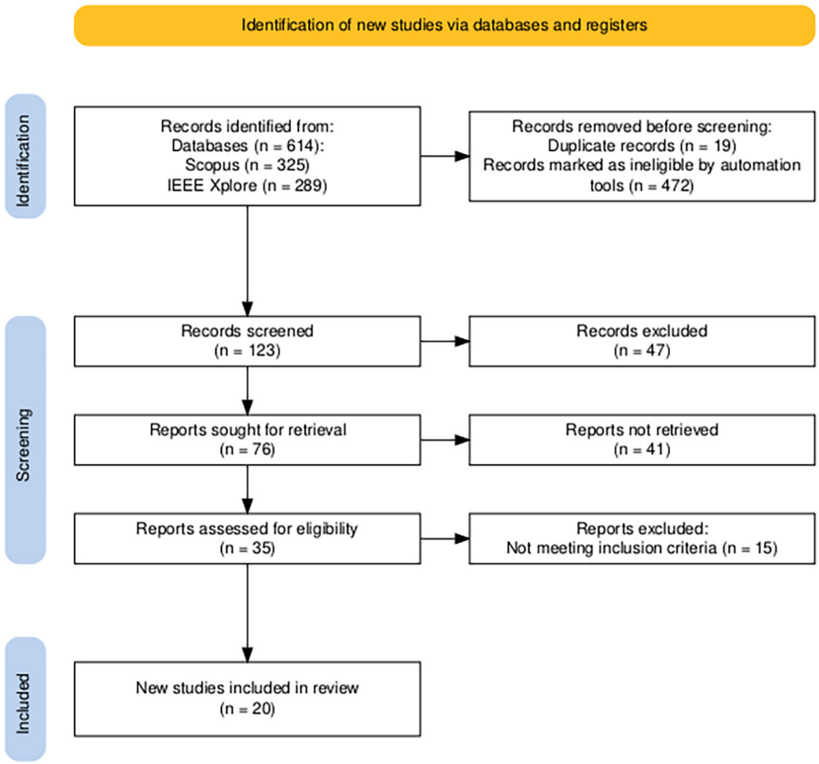

Fig. 1. PRISMA chart

Table 1. Inclusion and exclusion criteria

Inclusion	Exclusion
Studies in electrical engineering education	Studies outside electrical engineering
Virtual laboratories used as part of the learning process	Virtual laboratories without educational application
Empirical reporting of learning outcomes or learner perceptions	Studies without empirical educational evaluation

3 RESULTS

3.1 Electrical engineering topics addressed using virtual laboratories

The analysis shows that virtual laboratories have been implemented in various topics in electrical engineering learning, although the distribution is uneven. As shown in Figure 2, Electrical Machines is the most discussed; this finding indicates a strong focus on dynamic system behavior, complex visualization, and safety-related experiments. Furthermore, other topics such as electrical measurements, electronic circuits, and power electronics have moderate representation. This finding confirms that virtual laboratories are suitable for circuit-based learning and emphasizes the importance of measurement activities. Other topics, such as control systems, electrical energy, communication, energy conversion, and industrial electrical control, have the least representation. Overall, the analysis results show that existing research is still focused on basic courses. At the same time, more specific learning topics in electrical engineering remain underexplored, creating opportunities for future research.

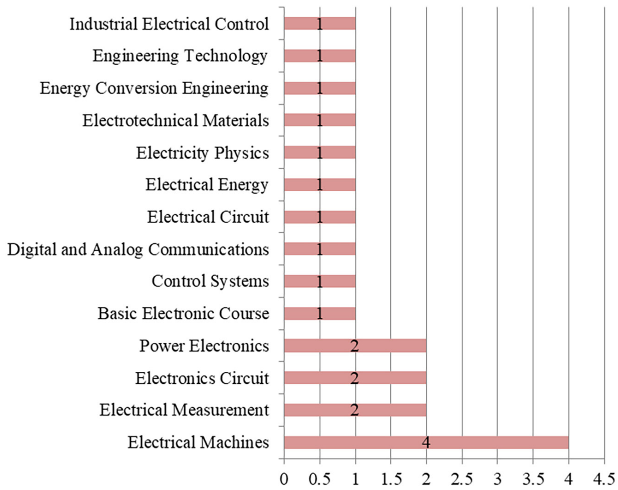

Fig. 2. Electrical engineering learning topics using virtual laboratories

3.2 Virtual laboratories used in electrical engineering learning

The results of this study indicate that various virtual laboratory platforms have been used in electrical engineering education, both general-purpose simulations and field-specific environments. As shown in Table 2, simulation software such as NI Multisim, MATLAB, LabVIEW, LTspice, and Proteus is predominantly used across various courses. NI Multisim demonstrates flexibility as it can be used in various courses such as electrical machines, electronic circuits, and industrial electrical control. MATLAB and LabVIEW, with their powerful modelling and control capabilities, can be applied in control systems and energy conversion engineering courses. Several studies also report the use of specialized virtual laboratories, such as PhET Interactive Simulations, the Falstad Circuit Simulator, and the Power Electronics Virtual Laboratory, for topic-specific learning. Emerging approaches, including augmented reality-based laboratories, are limited to specific contexts, indicating early exploration of immersive environments. Overall, the findings of this study indicate that the application of virtual laboratories in electrical engineering education still largely relies on established simulation software. At the same time, customized and immersive platforms have not yet been implemented across various topics in electrical engineering education.

Table 2. Virtual laboratory platforms used in electrical engineering education

Topics	Virtual Laboratory	References
Basic Electronic Course	Electric Lab	[19]
Control Systems	MATLAB Tinkercad	[23]
Digital and Analog Communications	TutorTims Simulator	[24]
Electrical Circuit	Falstad Circuit Simulator Virtual Instrument Systems in Reality	[25]
Electrical Energy	Dry Cell Microscopic Simulation	[26]
Electrical Machines	NI Multisim PSIM Virtual Laboratory of Motor DC	[27], [28], [29], [30], [31]

(Continued)

Table 2. Virtual laboratory platforms used in electrical engineering education *(Continued)*

Topics	Virtual Laboratory	References
Electrical Measurement	Mobile Virtual Laboraroty Proteus	[32], [33]
Electricity Physics	PhET Interactive Simulations Physics and Chemistry by Clear Learning	[34]
Electronics Circuit	3D-DCLab Ltspice NI Multisim	[35], [36]
Electrotechnical Materials	AR Virtual Lab	[37]
Energy Conversion Engineering	LabVIEW MATLAB	[38]
Engineering Technology	Virtual Renewable Energy Laboratory	[3]
Industrial Electrical Control	NI Multisim	[39]
Power Electronics	Power Electronics Virtual Laboratory Virtual Laboratory	[40]

3.3 Evaluation methods used in virtual laboratory studies for electrical engineering learning

The results of the study indicate that self-reporting-based instruments are the dominant evaluation method in studies of virtual laboratories in electrical engineering education. As shown in Figure 3, questionnaires are the most frequently used method (n = 14), reflecting a strong focus on learner perceptions and attitudes. Tests are used less often (n = 6) and mainly assess cognitive outcomes. Experimental reports (n = 2), real-time assessments (n = 1), and rubric-based assessments (n = 1) are rarely employed. Overall, these findings show a heavy reliance on questionnaires, while performance-based and process-oriented evaluation methods remain limited.

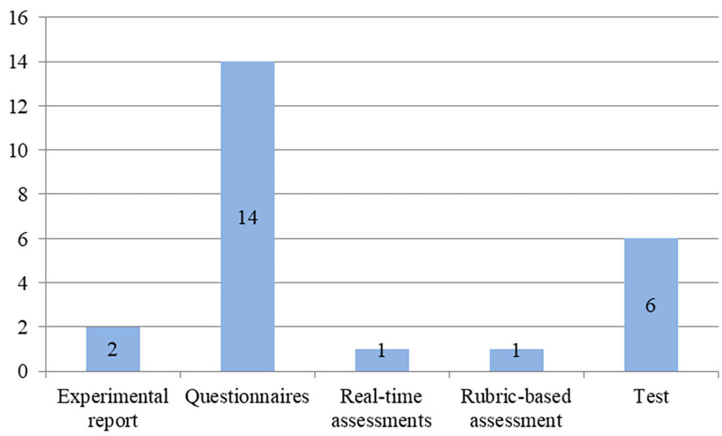

Fig. 3. Evaluation methods for virtual laboratory-based learning in electrical engineering

3.4 Categories of student learning outcomes in electrical engineering learning supported by virtual laboratories

The results show that virtual laboratory–supported electrical engineering studies report a wide range of student learning outcomes, with a strong emphasis on the cognitive domain. As shown in Figure 4, cognitive outcomes dominate, particularly knowledge (n = 3) and constructivist thinking (n = 2), along with various higher-order processes such as engagement, performance, creativity, and reflective thinking (each n = 1). Psychomotor outcomes are reported only marginally, limited to practical skills and virtual laboratory skills (each n = 1). Similarly, affective outcomes are underrepresented, with few studies examining interest, self-efficacy, or test anxiety (each n = 1). Several outcomes fall outside traditional domains and are grouped as other outcomes, including CDIO skills, general learning outcomes, and professional profiles (each n = 1). Another finding indicates that research findings related to technology acceptance, such as perceived usefulness, ease of use, and attitudes toward use, are also frequently reported. Overall, these findings indicate that previous research still prioritizes cognitive outcomes and technology acceptance, while psychomotor competencies, affective domains, and professional competencies have yet to receive sufficient attention.

3.5 Challenges in implementing virtual laboratories in electrical engineering education

The research findings identified various challenges in implementing virtual laboratories in electrical engineering education, grouped into five main categories, as shown in Figure 5. These include skills-related challenges, such as limited manual skill development and reduced hands-on experience due to decreased tactile interaction in the learning process. Furthermore, technical and infrastructure issues, such as connectivity, system compatibility, and device licensing constraints, emerged as major concerns. Other challenges include concerns about the validity and realism of simulations stemming from inaccurate modelling and ideal conditions. Furthermore, social and collaboration challenges such as reduced teamwork, limited support, and difficult remote interactions arise. Furthermore, operational and management challenges, such as large-scale group learning, steep learning curves, and server security risks, further hamper wider-scale implementation. Overall, these findings suggest that the challenges of virtual laboratories in electrical engineering education extend beyond technical limitations to include pedagogical, social, and managerial dimensions.

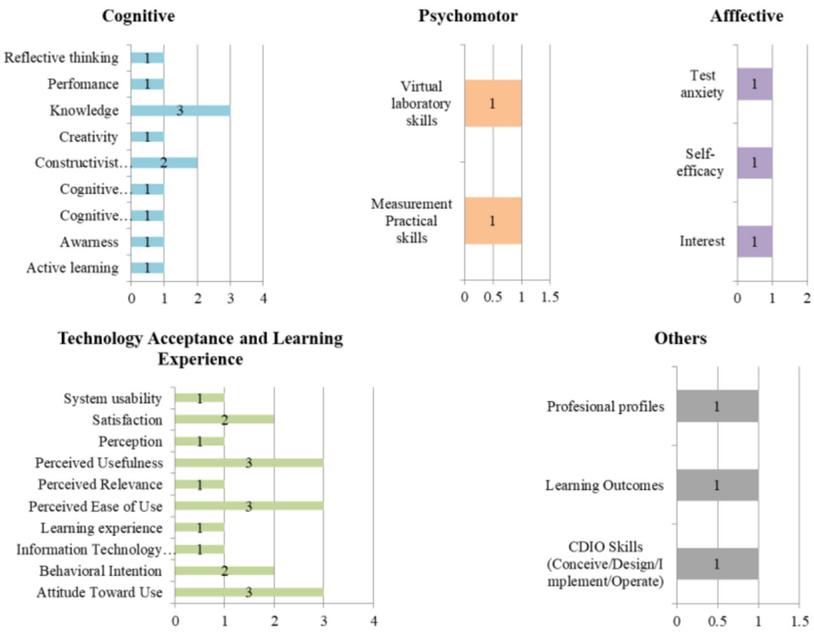

Fig. 4. Student learning outcome categories

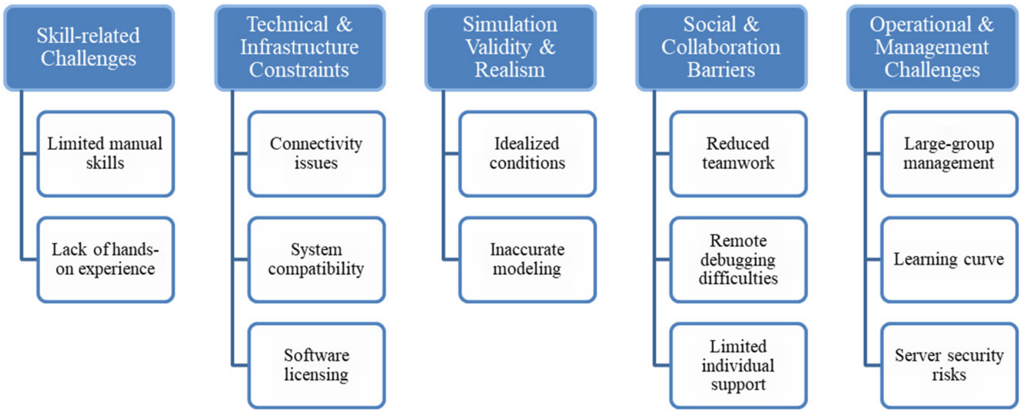

Fig. 5. Challenges in implementing virtual laboratories in electrical engineering education

4 DISCUSSION

4.1 Findings

This systematic literature review indicates that the implementation of virtual laboratories in electrical engineering education is characterized by selective pedagogical adoption and uneven methodological rigor. Studies focusing on fundamental domains such as electrical machines, circuit analysis, and power electronics suggest that virtual laboratories are used in learning, where safety risks, high equipment costs, and system complexity limit access to physical experiments. Previous studies have consistently reported results that virtual laboratories are effective in supporting conceptual understanding, system visualization, and exploratory learning [1], [28], [41]. However, the marginal representation of advanced, application-oriented fields, such as industrial electrical control, communication systems, and energy conversion engineering, suggests that the adoption of virtual laboratories has not fully aligned with the breadth of competencies required by contemporary electrical engineering curricula [15].

From a technological perspective, the dominance of established simulation platforms such as MATLAB, LabVIEW, Multisim, LTspice, and Proteus reflects the maturity and conservative evolution of the virtual laboratory ecosystem. These simulation software offer robust modelling, numerical analysis, and visualization capabilities that support implementation across a wide range of institutions [3], [42]. However, over-reliance on conventional simulators can limit the development of experiential and procedural learning. Recent research findings highlight the pedagogical capabilities of immersive and intelligent virtual laboratories, such as virtual reality, augmented reality, digital twins, and AI-powered instructional guides, which enhance realism, contextual scaffolding, and learner autonomy [5], [8], [10]. Despite these benefits, limited adoption suggests that institutional readiness, instructional design expertise, and infrastructure constraints remain crucial barriers to broader learning innovation [6].

The evaluation approaches used in the analyzed studies exhibit strong methodological inequities. Assessment practices are dominated by self-report questionnaires emphasizing learner perceptions, motivation, engagement, and technology acceptance. While these dimensions are important for understanding learner experiences and adoption behaviors [16], [17], they provide limited evidence of actual competency development. Performance-based assessments, real-time evaluations, and rubric-based measures are still relatively rare. Meta-analytic research findings reinforce this pattern, showing that virtual laboratories exert the strongest influence on learning motivation and engagement [12]. These findings highlight the persistent challenges associated with authentic laboratory competency in virtual learning environments.

In line with evaluation trends, reported learning outcomes are largely cognitive in nature. Knowledge acquisition, conceptual understanding, and constructivist thinking, such as those demonstrated by virtual laboratories, support abstract reasoning and exploratory learning [19], [33]. In contrast, psychomotor outcomes such as manual skills and physical interaction, and affective outcomes beyond motivation and anxiety reduction, are underrepresented. Although some studies suggest that virtual and distance laboratories can support the development of practical skills, particularly when the learning process is combined with real systems or digital twins [7], [14], the evidence supporting these findings remains very limited. Therefore, virtual laboratories are more appropriately used as a supplementary or preparatory tool rather than as a full replacement for physical laboratories.

The challenges identified in the reviewed literature underscore the multidimensional nature of virtual laboratory implementation. Limitations in skills, particularly the lack of tactile feedback and manual manipulation, remain fundamental concerns that must be addressed in engineering education. Technical and infrastructural constraints, such as connectivity issues, software licensing, system compatibility, and security risks, are frequently reported, particularly in large-scale or resource-constrained contexts [11], [18]. Furthermore, the reduced opportunities for collaboration and instructional support in virtual settings highlight the importance of pedagogical strategies that can foster social interaction and teamwork, such as paired learning, multiplayer virtual laboratories, and collaborative virtual environments [19], [43].

Overall, the research findings indicate that while virtual laboratories are effective in enhancing cognitive learning, student engagement, and accessibility in electrical engineering education, their implementation remains pedagogically limited and yields limited results. To strengthen the impact of virtual laboratory implementation in education, alignment between learning objectives, laboratory design, and assessment strategies, as well as the integration of immersive, intelligent, and collaborative technologies, is needed. Without such alignment, virtual laboratories will remain a peripheral innovation and cannot become a structurally embedded part of a sustainable engineering education ecosystem.

This study has limitations, such as using only the Scopus and IEEE Xplore databases and analyzing only relevant research published between 2021 and 2025, which increases relevance but limits the longitudinal perspective. Exclusion of studies due to the unavailability of full text and the heterogeneity of study designs, virtual laboratory types, and evaluation instruments further limits the depth and comparability of the synthesis. Another limitation is that the dominance of perception-based assessments biases the evidence toward cognitive and affective outcomes, while psychomotor and professional competencies remain underrepresented. Future research is expected to utilize broader databases, expand the timeframe, explore domains not yet represented in electrical engineering, and employ experimental and longitudinal designs with standardized, performance-oriented assessment frameworks. Future researchers are expected to pay particular attention to hybrid laboratory models and immersive or AI-powered virtual laboratories to address skill transfer and professional readiness better.

The research findings indicate that virtual laboratories are effective as a complement to the learning process, supporting conceptual understanding and preparatory skills, rather than as a complete replacement for physical laboratories. Educators should align the desired learning outcomes with the laboratories used and iterate on collaboration and support mechanisms to mitigate skill and interaction limitations. At the institutional level, balanced investments in infrastructure, faculty development, and instructional support are needed. For researchers, these results highlight the need for more rigorous, theoretically diverse studies and diverse methodologies to strengthen the evidence base on the impact of virtual laboratories in electrical engineering education.

5 CONCLUSION

This systematic literature review synthesizes current research on the implementation of virtual laboratories in electrical engineering education. It reveals that prior research has largely focused on foundational topics and relied on simulation-based environments. Results indicate that virtual laboratories are effective in supporting conceptual understanding and student engagement; however, evaluation approaches remain largely quantitative and perception-based, and are limited in reporting evaluations related to psychomotor skills and professional competency development. New technologies such as immersive environments and intelligent systems have not been widely or systematically adopted, but still show significant potential. Challenges related to skill acquisition, instructional design, and technical infrastructure suggest that virtual laboratories are more effective as supplementary learning environments than as substitutes for full-fledged physical laboratories. By providing a focused and up-to-date synthesis within the context of electrical engineering education, this review clarifies current research trends. It highlights the need for more rigorous, outcome-oriented, and pedagogically aligned investigations to advance the continued practice of virtual laboratories in education.

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