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Virtual laboratories and online learning in engineering education: a review

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ABSTRACT

The rapid expansion of virtual laboratories and online learning in engineering education, accelerated by the COVID-19 pandemic, has created an urgent need for clearer pedagogical guidance on how digital laboratory modalities should be used. This review addresses the unresolved educational problem of ensuring that virtual and remote laboratory environments support not only conceptual understanding but also practical laboratory skills and broader professional competencies. Using a structured review of recent empirical studies, systematic reviews, and meta-analyses, the paper synthesizes evidence on simulation-based laboratories, remote laboratories, immersive environments, and the wider online learning conditions that shape their effectiveness. The review finds that virtual laboratories are consistently effective for conceptual learning, visualization, flexibility, and access, while remote and immersive environments can strengthen authenticity and practical skill development when combined with active learning, multimodal assessment, and strong instructional support. However, persistent limitations remain in psychomotor skill development, assessment validity, accessibility, and institutional readiness. The review concludes that no single modality is sufficient on its own; rather, a hybrid model that pedagogically integrates virtual, remote, immersive, and physical laboratory experiences offers the most defensible pathway for meaningful and sustainable engineering laboratory education.

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1. INTRODUCTION

The shift from traditional classroom teaching to online teaching caused by the COVID-19 pandemic was a sudden and global transformation. Engineering programs around the world rapidly moved their courses and laboratories online, revealing both the potential and the limitations of digital delivery. Although virtual and remote laboratories are now widely used, a specific educational problem remains unresolved: engineering educators still lack clear pedagogical guidance on how digital laboratory environments can support both conceptual understanding and the practical, procedural, and professional competencies expected from laboratory education. This unresolved problem is especially important because laboratory learning in engineering is not limited to content acquisition; it also involves experimentation, troubleshooting, collaboration, safety awareness, and professional judgment [1]–[3].

Existing reviews have provided valuable insights into simulations, remote laboratories, virtual reality (VR), and online learning. However, prior work often compares methods in isolation rather than explaining how they can be pedagogically integrated across engineering curricula. Furthermore, the literature has expanded rapidly to include extended reality (XR), digital twins (DT), and artificial intelligence (AI)-assisted support, shifting the institutional focus from emergency substitutes to sustainable design principles. Therefore, recent research has fundamentally shifted the focus of inquiry. Rather than whether virtual laboratories and online learning may be used in engineering education (the answer to which is now clear), the critical question is how different methods should be combined, sequenced, and evaluated to support the development of engineering knowledge, practical skills, collaboration, ethics, and professionalism. This review provides a synthesis of recent developments in the area, a review of the current state of the art in terms of educational outcomes, a description of the major limitations of existing research, and recommendations for the effective integration of virtual laboratories and online learning in engineering education.

Additionally, this article employs a structured narrative review methodology to examine literature from many databases, including Scopus, Web of Science, ERIC, IEEE Xplore, and ScienceDirect, with an emphasis on research conducted between 2019 to 2025, as well as selected foundational works published prior to 2019 [4]–[7]. The search terms included "virtual laboratory", "remote laboratory", and "online laboratory", all of which are relevant to engineering education. The review favors peer-reviewed journal articles, substantial book chapters, and conference publications with an impact on engineering laboratory education. Included works address engineering education issues, multiple laboratory modalities, online learning environments (OLE), and implementation challenges, while omitting research that is unrelated to engineering or lacks an educational focus. The methodology prefers interpretive synthesis over preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodologies, foregoing formal quality rankings in favor of systematic reviews, meta-analyses, and contextually relevant empirical studies. The final synthesis categorizes findings by modality types, educational outcomes, enabling factors, ongoing challenges, implementation principles, and suggested future directions.

Finally, the key research question that this review will address is how virtual, remote, immersive, and physical laboratory modalities might be matched and blended to provide meaningful engineering learning outcomes. This review provides four major contributions: i) it synthesizes recent results from simulation-based, remote, immersive, and hybrid laboratory methodologies; ii) summarizes the findings of recent empirical investigations, systematic reviews, and meta-analyses on educational outcomes; iii) identifies persistent implementation barriers in assessment, accessibility, cost, experiential learning, and institutional preparation; and iv) provides design concepts for hybrid laboratory models that can be customized to various engineering contexts and resource constraints.

2. METHOD

This study summarized current research on online learning and virtual laboratories in engineering education using a structured narrative review. This method aimed to provide a comprehensive and critically structured knowledge of the ways in which different digital laboratory paradigms support engineering learning outcomes, the development of practical skills, and the general efficacy of education. A structured narrative review was preferred over statistical meta-analysis because of the variety of study types and factors in the field. In order to identify patterns, instructional tendencies, advantages, and limitations in the literature, it combined qualitative topic synthesis with systematic publication identification. However, this literature review focused on peer-reviewed articles, conference papers, systematic reviews, and meta-analyses published between 2020 and 2025, especially in the wake of the COVID-19 pandemic, and involved searches in major academic databases like Scopus, Web of Science, IEEE Xplore, and Google Scholar. "Virtual laboratories", "remote laboratories", "immersive learning", and similar concepts were among the search queries. Through earlier reference checking of important review publications, more research was found. Studies on engineering or closely related science, technology, engineering, and mathematics (STEM) education contexts that evaluated virtual, remote, or virtual laboratory environments in terms of educational results, student engagement, evaluation, and the development of practical skills were required to meet inclusion criteria. Publications that lacked actual detail or focused on technical platform development unrelated to educational evaluation were excluded.

Following basic searches, relevant titles and abstracts were assessed, and qualifying studies were then evaluated in detail. A thematic analysis of the literature was conducted, classifying research into key areas such immersive environments, remote laboratories, simulation-based laboratories, assessment procedures, and accessibility issues. The educational advantages, limitations, and pedagogical suggestions of several digital laboratory modalities were identified through a comparative analysis. Examining factors including conceptual knowledge, laboratory competencies, student involvement, and long-term sustainability, the assessment went beyond a single effectiveness metric. The structured narrative review enabled a comprehensive synthesis of recent advancements and pedagogical trends in virtual and online engineering laboratory instruction, although not offering a quantitative meta-analysis.

3. ONLINE LEARNING, VIRTUAL LABORATORIES, AND MODALITY CHOICE

Conceptual clarity is a useful term in art. In engineering education, terms like recorded lectures or learning management systems (LMS) do not reflect what online means. It refers to an ecosystem that includes synchronous or asynchronous training, simulations, remote instrument access, immersive settings, collaborative platforms, analytics, digital evaluation, and methodical student support. Similarly, "virtual laboratory" is too broad to be a single category. The literature refers to at least three broad categories of laboratory practices: simulation-based and virtual laboratories (whether for simulation, remote access to physical equipment, or mixed or cross-reality) that pair together digital and material aspects [1]–[5], [6]–[14].

Simulation-based virtual laboratories often provide students with a software-mediated environment in which variables can be adjusted, processes made visible, and experiments repeated to fit what would otherwise be time, safety, or material limits in physical laboratories. Their educational return is particularly apparent for topics that are abstract, multiscale, invisible, hazardous, or too expensive to reproduce in physical form [2]–[5]. Remote laboratories are related, but differ in one important way: the experiment is physically real, but the interface is networked. Students control real equipment, receive authentic data, and even encounter some of the nonideal behavior of actual systems, while no longer being geographically present in the laboratory [1], [3]–[5].

Mixed and cross-reality models attempt to bridge digital and material concepts by serving physical experiments (or lab equipment) with digital visualization or simulation, synchronous support, or immersive interfaces [8], [10]. These contrasts are not only intellectual, because, in the end, the appropriate comparison is not "online" vs "face-to-face", as a historically considered. Each modality enables and limits specific types of learning. Simulation-based laboratories encourage repetition, immediate feedback, and conceptual experimentation. Remote laboratories tend to preserve the authenticity of apparatus and data, but they may limit exploratory spontaneity, tactile interaction, and flexibility in scheduling. Cross-reality and hybrid design "distribute learning functions across a constellation of modes, rather than forcing a monologic mode to 'do it all' and 'do it better'" [8], [10], [13], [14].

Accordingly, recent reviews reject a one-size-fits-all approach entirely. The defensible instructional question is which mode or modes (or sequence, as engage then reflect) is most appropriate for the intended learning objectives, the profile of students, the resources at hand, and the disciplinary contexts concerned. The discussion has matured from modality advocacy to pedagogical fit. Pedagogical design, then, not technology, occupies center stage in the conversation. More sociotechnical but also sociotechnical-pedagogical approaches stress that online laboratories will be shaped by, among other things, assessment, support structure, interaction patterns, discipline, and institutional conditions [7]. In this approach, the usefulness of virtual laboratories and online learning is not unique to the software or technology itself, but rather in the types of engineering learning that they facilitate or constrain. These digital modalities allow engineering students to interact with interactive simulations, real-time remote experimentation, and immersive visualization technologies, thereby promoting important educational outcomes such as conceptual understanding, practical skill development, problem-solving ability, and collaborative learning. The framework also emphasizes implementation factors, such as technology infrastructure, enrollment, accessibility, practical competency evaluation, and instructor training, all of which are essential for effective engineering education deployment. Figure 1 depicts the conceptual framework of virtual laboratories and online learning in engineering education.

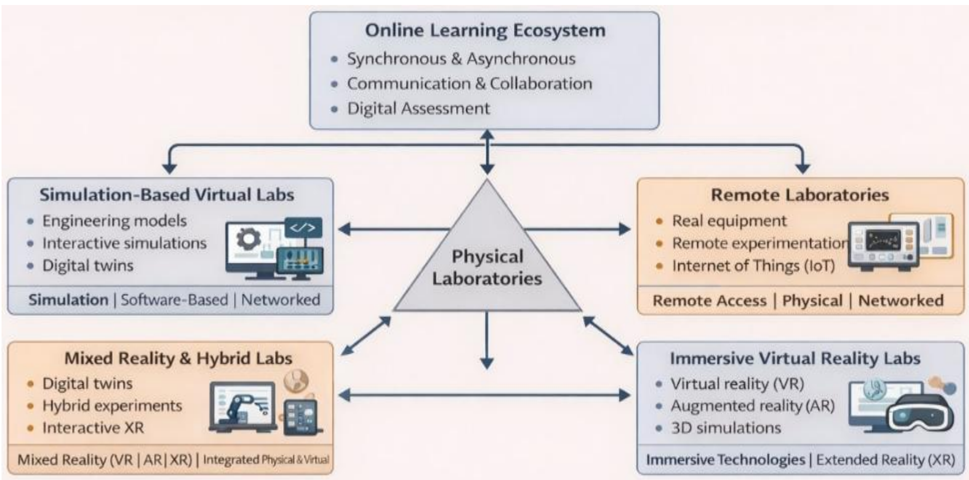

Figure 1. Conceptual framework of virtual laboratories and online learning in engineering education

4. EDUCATIONAL OUTCOMES OF VIRTUAL AND ONLINE LABORATORY EXPERIENCES
4.1. Comparative evidence on knowledge and skills
The strongest current evidence supports the use of virtual and remote laboratories as effective tools for developing concepts and ideas. This research emphasizes visualization, model-based reasoning, parameter analysis, and iterative experimental design, which can be achieved under non-traditional laboratory conditions. Comparative studies in engineering further support earlier conclusions that virtual laboratories are useful as supplements to in-person training and, in some cases, suitable substitutes for specific learning objectives. For example, study by Behera *et al.* [15] found that incorporating a virtual optics laboratory into classroom instruction improved students' understanding and their access to course information. A similar finding was noted by May *et al.* [16] who indicated that a combination of hands on and virtual labs was a superior method for achieving both the acquisition of knowledge and the development of skills compared to utilizing one type of lab environment exclusively. Furthermore, studies involving simulation of battery education and electrical measurement tasks reinforced the idea that simulations can facilitate understanding but do not preclude the need for hands-on experience when procedures and instrumentation require high levels of procedural nuance and instrumental proficiency [17], [18].

Examples of application oriented virtual lab design were shown to be successful in facilitating laboratory learning experiences during periods of disruption as well as being utilized after the disruptions had ceased [19], [20]. Recent reviews provide a higher level of evidence and support the findings discussed. Nikolic *et al.* [20] assessed the implementation of assessments in remote, simulated, and traditional engineering labs and found significant variation in how assessments were implemented and that the claims of equivalence were highly dependent on what was being measured. Frady [21] also performed a review and concluded that virtual labs can be used to successfully support engineering pedagogy; however, the advantages of virtual labs are not consistent across all of the different learning objectives. Kapilan *et al.* [12] published a meta-analysis that combined data from 46 studies from 22 publications. They found a positive overall effect of virtual labs on the performance of engineering students, thus providing additional empirical support that the educational benefits of virtual laboratory environments have expanded significantly since last decade. On the other hand, the literature reviewed by McAlister *et al.* [13] and Howcroft and Mercer [14] indicate that there continue to exist challenges associated with delivering fully online engineering education, particularly when attempting to develop practical fluency, professional judgment and real world decision-making under conditions of uncertainty.

4.2. Remote laboratories and authentic experimentation
Remote labs have a unique advantage due to the fact that they maintain the use of actual lab equipment, but relax the constraint of having to physically share space. The benefit of remote labs stems from the combination of using authentic data, seeing how a physical system behaves, and increased accessibility for students. Remote labs can provide flexible ways to allow many students to use expensive or highly specialized equipment as well as create the ability for distributed programs to run and increase the utilization of resources at institutions [21]. Remote labs allow students to experience the non-ideal behavior of real systems. However, they do not automatically improve student engagement.

However, Li and Liang [22] discussed the use of virtual laboratories in engineering education is becoming more popular but has not been well researched. This is a meta-analysis of 46 studies from 709 publications that found that the performance of engineering students in virtual labs is significantly better than that of their peers in real labs with a meta effect size of 0.686. Notably, they are able to improve learning motivation (effect size of 3.571) and engagement (2.888), which indicates their ability in creating student involvement in learning. Virtual labs can be used as a supplementary tool to the hands-on labs, and should be used in conjunction with hands on labs in order to effectively develop engineering education. Research by Tomeo-Reyes *et al.* [23] reported that student engagement depends mainly on the active learning methods used in the course, rather than only on access to remote equipment. According to the authors, "open ended" assignments, "preparation" tasks, working together, holding "progress meeting", receiving "formative" feedback, and writing "reflective reports" helped students move away from simply operating apparatus and toward the practice of transferring theoretical knowledge into practical application. Similarly, Sertu *et al.* [24] found that guidance levels are important in virtual engineering environments. The balance between user autonomy and support should be designed carefully by the system developer rather than left entirely to the user. Overall, these studies demonstrate that remote authenticity is only useful in a pedagogical sense when combined with instructional design [24]–[30].

4.3. Immersive environments, virtual reality, and extended reality
Early reviews identified a growing use of VR laboratories in engineering education to improve student learning outcomes related to spatial reasoning, visualization, and hazardous practices [31]–[33].

Subsequently, research studies demonstrated the effectiveness of utilizing immersive VR for enhancing engagement, sense of presence, perceived realism and the ability to demonstrate complex or difficult to access phenomena [34]–[39]. Recent research on VR-based learning experiences has received greater critical and theoretical attention. For example, Oje *et al.* [39] stated that many studies on VR in engineering education lack a strong theoretical basis for explaining how VR influences student learning. They argued that VR should be evaluated using multimedia learning theories rather than focusing only on the novelty of the technology. Furthermore, Khlaif *et al*. [40] illustrated that the implementation of XR-based systems in engineering education depend on whether instructors perceive their educational context as having adequate resources for implementing XR (such as computer hardware, software, and internet connectivity), professional development to utilize XR systems and if there is social support from peers or administration to implement XR-based systems. In other words, the success of XR-based learning environments is determined by the degree to which institutions are ready to implement XR, as well as how effectively educators are able to use XR to enhance student learning.

A meta-analysis of the existing research provides a more objective analysis of the impact of VR on student learning outcomes. Yang *et al.* [41] conducted a meta-analysis of 37 empirical studies focused on the impact of VR on practical skills, and found that VR had a moderate positive effect on practical skills for students in science and engineering education, with a higher positive effect when VR was used in conjunction with traditional methods of instruction as opposed to being used as a standalone substitute for traditional instruction. Negahban [42] review of simulation in engineering education noted that although immersive simulated environments have great promise, there is currently insufficient consideration of learning theory and insufficient assessment of the effectiveness of these simulated environments. Lampropoulos *et al.* [43] conducted a scoping review of VR use in engineering education and included 342 studies. They found that VR can improve student engagement and interaction, support the development of practical skills, enhance design visualization, and facilitate collaborative learning. They also noted that replacing physical laboratories with VR may offer advantages such as greater flexibility, lower infrastructure costs, and higher scalability. However, these benefits should be interpreted cautiously. Although lower marginal costs and improved scalability may reduce some of the financial burden of developing and maintaining VR-based learning environments, they do not eliminate the need for significant investment and development to create realistic simulations. Such simulations are necessary to provide students with a level of tactile authenticity comparable to hands-on work with physical materials.

4.4. Digital twins and emerging simulation ecologies

One major emerging trend in engineering education is the integration of digital twin technology, as well as virtual game-like environments into the classroom. Through digital twin and web-based virtual gaming technology, online learning in construction management and engineering can provide students with interactive learning experiences with dynamic and representative models of engineering systems [44]. In education, a digital twin is most valuable because it allows students to relate theoretical, model-based concepts to real operational data, observed system behavior, and potentially real-time performance feedback. This capability can support more authentic simulation environments, particularly in manufacturing, construction, control, and systems engineering. Although interest in DT is increasing, they are still not widely adopted or well-integrated into pedagogical approaches. In instructional settings, DT are likely to be most effective when they are used to promote systems thinking, scenario planning, and decision-making. Ultimately, as with other emerging technologies, whether DT help students develop meaningful engineering reasoning will depend on how students interact with the technology. Table 1 (in Appendix) depicts the educational outcomes, strengths, limitations, and design implications emerging across the reviewed modalities.

5. ONLINE LEARNING CONDITIONS SURROUNDING LABORATORY SUCCESS

The success of virtual labs does not occur in a vacuum. The success of the lab depends upon the overall environment of the OLE where it exists. There is an increasing trend toward adopting an Education 4.0 approach to engineering education. In this model, all aspects of curricula including the competencies and skills being taught, how learning occurs, the role of information and communications technologies (ICT), and the resources supporting both teaching and learning are considered to be interconnected [45]. Understanding the relationships among these components help explain why two educational institutions with virtually identical laboratory equipment will yield different results from their students.

It has been shown repeatedly that the extent to which students will accept online learning opportunities is directly related to the degree to which the requirements of the task at hand are supported by the technological capabilities of the system. For example, Navarro *et al.* [46] demonstrated that the level of satisfaction of engineering students with LMS during the COVID-19 pandemic was determined by both the task-technology fit and the perceived utility and ease of use of the LMS. Therefore, if students perceive that the platform supports the work they are required to complete, then they are more likely to see value in using online laboratories and/or digital course environments. Another important determinant of successful online learning is the degree to which students are able to self-regulate their own learning behaviors. Watson *et al.* [47] found that self-directed learning readiness is a significant predictor of undergraduate engineering students' experience with online learning, particularly when students have to manage their own pace, solve problems independently, and engage in distributed forms of participation. Self-directed learning readiness is not simply an abstract concept. Rather, it is an actual capability that some students possess while others do not. Online laboratories assume that students will have flexible schedules and repeated access to the platforms; however, such flexibility can also create liability for students who lack time management strategies, confidence, or clear expectations regarding their responsibilities.

Finally, the social and motivational aspects of online learning also play a significant role in shaping students' experiences with online learning. Sung and Huang [48] found that the online STEM learning experiences of women engineering students are influenced significantly by the motivational design of the learning activities, with confidence and attention being two of the most influential categories of design. Nikolic *et al.* [49] found that the quality of interaction, the services provided by the OLE, the assessment tools used in the OLE, and the quality of the technology used in the OLE were all significant predictors of students' satisfaction with online learning. Deriba *et al.* [50] systematic review integrated these observations into four general categories of acceptance factors: technology-related, individual-related, social/environmental, and outcome-related. Such factors include reliable technology, motivation, self-directed learning, peer and instructor support, perceived usefulness, and satisfaction with outcomes all contribute to the degree to which online learning is seen as empowering or alienating.

Therefore, understanding the factors that influence students' perceptions of virtual laboratories is essential for interpreting results from studies involving online laboratory research. Students' dissatisfaction with online laboratories does not always reflect only dissatisfaction with the laboratory mode itself. Such dissatisfaction may result from inadequate social support, ineffective communication, poor service quality, unreliable connectivity, lack of confidence, or inappropriate assessment structures [3], [51], [52]. On the other hand, when students are satisfied with virtual laboratories, it is usually because the overall OLE in which they exist provides support for the development of guidance, interaction, and motivation. These digital modalities enable engineering students to engage with interactive simulations, real-time remote experimentation, and immersive visualization technologies, thereby supporting key educational outcomes such as conceptual understanding, practical skill development, problem-solving ability, and collaborative learning. The framework also highlights implementation considerations, including technological infrastructure, student engagement, accessibility, assessment of practical competencies, and instructor training required for effective deployment in engineering education. Figure 2 illustrates online learning conditions surrounding laboratory success in engineering education.

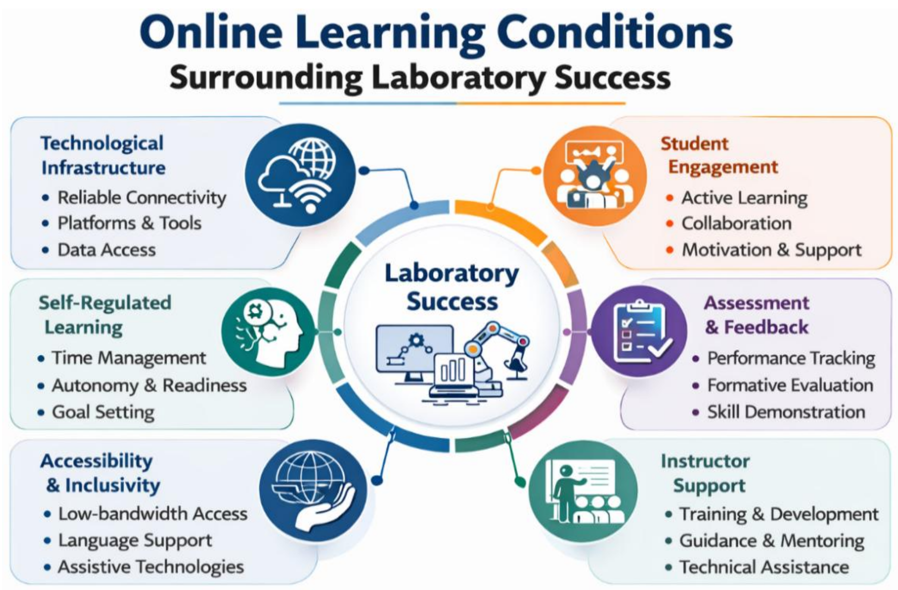

Figure 2. Online learning conditions surrounding laboratory success in engineering education

6. PERSISTENT CHALLENGES AND LIMITATIONS

At first, although virtual and remote laboratories have addressed many limitations in engineering education, several challenges still remain. Virtual and simulated laboratories can provide a useful alternative for learning some aspects of experimental science and engineering. However, they cannot fully replace hands-on experience, tactile and haptic feedback, procedural fluency, or troubleshooting with imperfect physical systems. Comparative studies and reviews show that virtual laboratories are especially effective for improving conceptual understanding and representational learning. However, the same studies also show that psychomotor skills and tacit practical knowledge are more difficult to develop through digital environments [16]–[18]. This does not imply that virtual laboratory-based engineering education is inherently less effective. Rather, it indicates that laboratory learning is multidimensional, and that certain dimensions may be less amenable to digitization than others.

Second, assessment continues to be one of the most challenging areas in which to make meaningful progress. Nikolic *et al.* [20] systematic review reports that engineering laboratory studies have employed a wide variety of assessment methods, including post-test evaluations, student-generated reports, and self-reported measures, but have generally provided limited direct evidence of students' laboratory competency. Similarly, Elmoazen *et al.* [53] reported a similar lack of consensus in their review of empirical research into the application of learning analytics (LA) in virtual laboratories. Their review suggested that applications of LA are generally relatively small scale, exploratory, and primarily based upon log-file analysis, with little agreement on what constitutes an effective dashboard, indicator(s), or design standard. As a result, the absence of a shared understanding of how to assess success in online laboratory settings is likely to make it harder to interpret research findings. This challenge is intensified by evidence from work on laboratory learning objectives, which suggests that online, blended, and traditional modes of instruction may emphasize different outcomes. It also indicates that cognitive, psychomotor, and affective learning domains may not be addressed to the same extent in both instructional implementation and evaluation [44], [45].

Third, although there is growing awareness of the importance of accessibility and inclusion, these topics have received limited systematic attention in the context of virtual laboratory-based engineering education. Deriba *et al.* [50] review of accessibility in virtual laboratories found that accessibility is often defined too narrowly, and that assessments of accessibility are still carried out using inconsistent approaches [46]–[50]. Ensuring accessibility and inclusion goes beyond meeting disability laws and regulations. Additional considerations include whether virtual laboratory interfaces work effectively with a range of assistive technologies, function under different bandwidth conditions, and support diverse languages and cultural contexts. The design should also accommodate learners with different rates of completion, provide multiple forms of representation, and offer sufficient support for user interaction [54]. In addition, since much of the instrumentation and data presentation in engineering education involve complex software, hardware, and display components, poor design of the user interfaces of these systems can quickly become a barrier to participation and achievement.

Fourth, there are considerable technological, financial, and organizational obstacles to widespread implementation of virtual lab-based engineering education. While virtual and remote laboratory-based engineering education may reduce material costs and increase access, they nevertheless necessitate significant investment in infrastructure, software development, maintenance, and technical support [10], [11], [15]–[17], [31], [32], [35], [44], [51]–[54]. Without ongoing pedagogical and institutional support, virtual and remote laboratory systems can devolve into fragile learning environments characterized by interface complexity, scheduling conflicts, inconsistent connectivity, and increased the workload of educators.

Finally, poorly planned online laboratory teaching could negatively impact the overall experiential quality of engineering education. Laboratory learning is more than just operating equipment and producing the correct output; it also includes judgment, teamwork, communication, perseverance, safety culture, and professional identity. Tembrevilla *et al.* [55] study of experiential learning in engineering education highlights that it is contextual, action-oriented, and often socially influenced [55], [56]. Table 2 (in Appendix) depicts the persistent challenges and limitations in virtual laboratory–based engineering education.

7. BEST PRACTICES FOR IMPLEMENTATION

Designing effective hybrid lab experiences depends on key design principles rather than selecting a single best platform. First, design must be goal-driven. Each activity should target specific cognitive or psychomotor objectives. Second, design must focus on modality complementarity. As noted previously, hybrid sequences reduce cognitive overload and optimize limited face-to-face time [20], [23], [55]. Third, design must be based on guided active learning. Virtual environments require students to make predictions and decisions, paired with carefully calibrated instructional guidance [32], [33]. Fourth, design must emphasize authentic, multimodal assessment. Evaluative criteria should integrate conceptual checks, troubleshooting tasks, and performance demonstrations, supported transparently by LA [20], [51]–[53]. Fifth, the design must include robust online learning support. Faculty require ongoing professional development in online pedagogy, not just software operation [17], [40]. Sixth, design must be accessible by design, prioritizing inclusivity from the initial stages rather than as a retroactive compliance measure [57]–[59].

8. DISCUSSION AND IMPLICATIONS

The literature consistently indicates that the instructional usefulness of virtual laboratories is determined by pedagogical alignment rather than technological innovation. Simulation-based environments excel at conceptual visualization, whereas remote and immersive environments provide the authenticity required for practical decision-making. However, a critical theoretical tension exists in the current literature between the scalability of digital laboratories and the preservation of authentic experiential learning. While institutional stakeholders often view virtual labs as a cost-effective, scalable alternative, educational researchers warn that without careful hybrid integration, the broader experiential dimensions of engineering may be lost. Furthermore, the persistent reliance on varied, non-standardized assessment methods makes claims of full equivalence between digital and physical labs difficult to substantiate. These findings have important implications for engineering education and the broader educational community. For the discipline, they shift the focus from the question of whether virtual laboratories can replace physical laboratories to the more practical issue of how to combine different laboratory modes within coherent curricula. The results also suggest that institutions should align investment in digital laboratory infrastructure with investment in instructional design, assessment, accessibility, faculty development, and student support. For the broader community, the findings support more flexible and inclusive engineering education models that, when implemented thoughtfully, can expand access while maintaining educational quality [60].

9. FUTURE DIRECTION

The near future of engineering education will likely be defined by a “hybrid-first” approach. XR and DT will continue to grow in utility for visualizing complex systems and reviewing data-rich operational models [29], [34]. However, the true impact of these technologies will depend on whether researchers move beyond novelty-driven studies to address unresolved theoretical contradictions, such as the gap between simulated proficiency and real-world application. Another vital area of growth is LA. The field urgently requires standardized frameworks that prioritize student privacy and demonstrably improve learning outcomes, rather than merely increase data collection [51]. AI-assisted support must also be approached with caution, ensuring that it scaffolds rather than replaces the student’s independent reasoning process [24], [51]. Finally, engineering education research must broaden its evaluative scope. Future empirical work must shift from measuring short-term satisfaction to evaluating the long-term transfer of digital skills into physical design practice. Investigating who benefits most from specific methods, under what resource conditions, and ensuring equity remains a primary criterion for quality engineering education [21], [24], [43], [54], [55]. However, Figure 3 illustrates future directions of virtual laboratories and online learning in engineering education. Table 3 shows the key implementation strategies for design principles for engineering education.

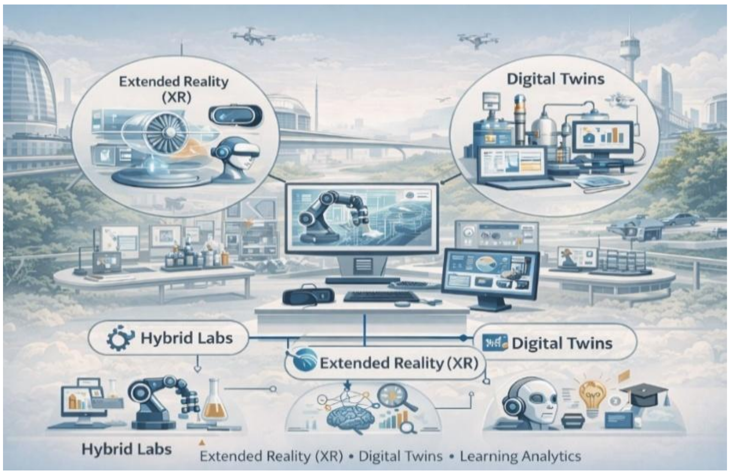

Figure 3. Future directions of virtual laboratories and online learning in engineering education

Table 3. Key implementation strategies for design principles for engineering education

Design principle	Description	Key implementation strategies
Goal-driven laboratory design	Laboratory activities should be aligned with clearly defined learning objectives across cognitive, psychomotor, and affective domains rather than being determined solely by available technology.	- Use simulation-based labs for conceptual understanding. - Use remote or physical labs for instrumentation handling and calibration. - Apply sequenced learning approaches for integrated professional reasoning.
Modality complementarity	Hybrid laboratory experiences should integrate multiple modalities to leverage the strengths of each learning environment.	- Virtual preparation activities. - Remote experimentation using real equipment. - Immersive rehearsal or training environments. - Physical laboratory validation or capstone application.
Guided active learning	Virtual and remote laboratories should promote active engagement through inquiry-based and collaborative tasks rather than passive procedural execution.	- Encourage prediction and hypothesis generation. - Require explanation and comparison of results. - Support collaborative problem solving and reflective learning. - Balance inquiry with appropriate instructional guidance.
Authentic multimodal assessment	Laboratory assessment should capture both conceptual understanding and practical problem-solving processes using diverse evaluation methods.	- Conceptual knowledge checks. - Oral explanations and troubleshooting tasks. - Design notebooks and reflective commentary. - Group artifacts and performance demonstrations. - Use LA to complement instructor evaluation.
Robust online learning support	Successful virtual laboratory environments require strong instructional presence, technical reliability, and clear communication structures.	- Orientation to digital tools and resources. - Clear expectations and communication channels. - Rapid technical support and feedback mechanisms. - Faculty development in online pedagogy and inclusive teaching.
Accessibility by design	Accessibility considerations should be embedded from the beginning of the design process to ensure equitable participation in online laboratories.	- Screen-reader compatibility and keyboard navigation. - Captioned multimedia and alternative visual formats. - Low-bandwidth access options. - Flexible scheduling and clear instructional language.
Sustainable infrastructure and governance	Long-term sustainability requires institutional planning, resource management, and collaborative governance frameworks.	- Long-term hardware and software maintenance. - Interoperability across platforms. - Privacy and data stewardship policies. - Shared laboratory platforms and cross-institutional collaboration.

10. CONCLUSION

Physical laboratories are still an important aspect of engineering education, but research suggests that virtual laboratories and online learning can make significant contributions when used for clearly defined pedagogical goals. The review's main finding is that different laboratory methods support different learning outcomes. Persistent issues remain in psychomotor skill development, assessment validity, and institutional planning. As a result, the key conclusion is not that one modality should be replaced by another, but that hybrid laboratory models provide the most educationally sound approach by distributing learning functions among virtual, remote, immersive, and physical environments. Looking ahead, the most important task for engineering education is to create evidence-informed hybrid ecosystems that are pedagogically rigorous, accessible across contexts, and adaptable to future technological and institutional changes.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this paper.

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APPENDIX

Table 1. Educational outcomes, strengths, limitations, and design implications emerging across the reviewed modalities

Technology/modality	Educational outcome	Strengths	Limitations	Recommendations
Simulation-based virtual laboratories	Conceptual understanding, visualization, repeated practice	Flexible, scalable, safe for hazardous or costly phenomena	Limited tactile authenticity and partial coverage of psychomotor skills	Use for preparation, conceptual experimentation, and abstract phenomena
Remote laboratories	Authentic data, instrument familiarity, practical reasoning	Access to real equipment and distributed participation	Scheduling constraints, weaker tactile interaction, engagement not automatic	Pair with active learning, preparation tasks, and formative feedback
VR/AR/XR environments	Spatial reasoning, engagement, safe rehearsal of complex or hazardous tasks	High immersion, strong visualization, useful for inaccessible systems	Resource-intensive, variable theoretical grounding, novelty effects possible	Combine with conventional instruction and evaluate beyond perceived realism
DT and simulation ecologies	Systems thinking, scenario analysis, data-rich decision making	Links models with operational behavior and dynamic system representations	Pedagogical models are still emerging and empirical evidence is limited	Use for decision-focused tasks in manufacturing, construction, and control contexts
Online learning ecosystem and support structures	Acceptance, satisfaction, self-regulation, persistence	Can extend access and flexibility across programs	Highly sensitive to connectivity, service quality, and support disparities	Invest in orientation, instructor presence, technical support, and inclusive design
Hybrid integration of modalities	Broader cognitive, practical, and professional outcomes	Leverages complementarity across modalities	Requires careful coordination, assessment design, and institutional capacity	Sequence modalities according to learning outcomes and local resource conditions

Table 2. Persistent challenges and limitations in virtual laboratory–based engineering education

Challenge category	Key issues identified in the literature	Implications for engineering education
Limited replication of embodied laboratory skills	Virtual and simulated laboratories can effectively support conceptual understanding and representation of engineering phenomena; however, they often struggle to reproduce embodied manipulation, tactile and haptic feedback, procedural fluency, and troubleshooting in imperfect physical systems.	Digital laboratories may not fully replace hands-on environments for developing psychomotor competencies and tacit laboratory skills. Hybrid or blended laboratory models may therefore be necessary.
Assessment challenges in online laboratory environments	Studies report a lack of consistent assessment approaches. Common methods include post-tests, laboratory reports, and self-reported evaluations rather than direct demonstrations of laboratory competence. LA applications remain exploratory and largely based on log-file analysis without established standards.	Difficulty in evaluating authentic laboratory competencies and comparing learning outcomes across modalities. The absence of standardized metrics complicates interpretation of educational effectiveness.
Accessibility and inclusion limitations	Accessibility is often narrowly interpreted and inconsistently evaluated. Challenges include compatibility with assistive technologies, language diversity, bandwidth limitations, interface design, and equitable participation for students with different learning needs.	Poorly designed systems can create barriers to participation and learning. Inclusive design principles and accessibility standards are required to ensure equitable access to virtual laboratory environments.

Table 2. Persistent challenges and limitations in virtual laboratory–based engineering education (*continued*)

Challenge category	Key issues identified in the literature	Implications for engineering education
Technological and organizational barriers	Implementation requires significant investment in infrastructure, software development, maintenance, and technical support. Faculty must redesign experiments, instructional materials, and assessments for virtual environments.	Without institutional support, virtual laboratories may become fragile learning systems characterized by technical issues, scheduling conflicts, and increased instructor workload.
Reduction of experiential learning elements	Laboratory education involves collaboration, communication, judgment, perseverance, and safety awareness. Poorly designed online laboratories may reduce these experiences to passive observation or isolated interaction with simulations.	Loss of the broader experiential dimension of engineering education, including professional identity formation and collaborative problem-solving.

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