Iraqi Journal for Computer Science and Mathematics

Volume 5 | Issue 4 Article 17

2024

E-Learning Management Technology Integration for Laboratory Usage

Mohammed Khaleel Hussein
Department of Planning, Directorate of Private University Education, Ministry of Higher Education and Scientific Research, Baghdad, Iraq, mohammedkhaleel@scrd-gate.gov.iq

Mohammed Ahmed Subhi
Department of Planning, Directorate of Private University Education, Ministry of Higher Education and Scientific Research, Baghdad, Iraq AND Balad Technical Institute, Middle Technical University, Baghdad, Iraq, mohammed-ahmed@mtu.edu.iq

Saleh Mahdi Mohammed
Department of Computer Technology Engineering, Technical College, Imam Ja'afar Al-Sadiq University, Baghdad, Iraq, saleh.mahdi@ijsu.edu.iq

Mayasah Al-khateeb
College of Economic and Administration, Al Iraqia University, Baghdad, Iraq, mayassam_80@yahoo.com

Recommended Citation

Hussein, Mohammed Khaleel; Subhi, Mohammed Ahmed; Mohammed, Saleh Mahdi; and Al-khateeb, Mayasah (2024) "E-Learning Management Technology Integration for Laboratory Usage," *Iraqi Journal for Computer Science and Mathematics*: Vol. 5: Iss. 4, Article 17.
DOI: https://doi.org/10.52866/2788-7421.1000
Available at: https://ijcsm.researchcommons.org/ijcsm/vol5/iss4/17

IRAQI JOURNAL FOR COMPUTER SCIENCE AND MATHEMATICS 2024;5:208–219

RESEARCH ARTICLE

E-Learning Management Technology Integration for Laboratory Usage

Mohammed Khaleel Hussein [a], **Mohammed Ahmed Subhi** [a,b,*], **Saleh Mahdi Mohammed** [c], **Mayasah Al-khateeb** [d]

[a] Department of Planning, Directorate of Private University Education, Ministry of Higher Education and Scientific Research, Baghdad, Iraq
[b] Balad Technical Institute, Middle Technical University, Baghdad, Iraq
[c] Department of Computer Technology Engineering, Technical College, Imam Ja'afar Al-Sadiq University, Baghdad, Iraq
[d] College of Economic and Administration, Al Iraqia University, Baghdad, Iraq

ABSTRACT

E-learning systems have transformed educational sectors and more interestingly, the use of these educational platforms for laboratory-based practices has been trending in the last couple of years. Laboratory-usage e-learning system has various tremendous benefits such as the skill of accessibility utilization and practical experimentation simulation. Several intelligent tasks still need to be tackled to make the most of it. One of the biggest problems is how to recreate hands-on experience in a virtual or remote environment. Some e-learning systems offer simulations and virtual experiments but may also require additional tactile feedback through interaction with physical equipment for this challenge, it is necessary to work toward creating more realistic virtual simulations and using haptic technologies that improve the realism of experience senses. Training instructors to exploit the system effectively as well as modifying instructional strategies and providing guidance for students during virtual or remote engagement and clear instructions or guidelines for using the e-learning platform should be provided to students for effective understanding and learning throughout the process. The continuous evaluation and improvement in the performance of these systems must be focused on making e-learning systems more effective for laboratory use. Feedback from instructors and students regularly would help to pinpoint what can be improved. Insights from research studies and evaluations can also inform the role of different approaches, instructional strategies, and technologies in laboratory education. In this article, we introduce e-learning systems for laboratory usage and then present their challenges and how they can be addressed.

Keywords: E-learning, Laboratory, Virtual labs, Remote labs, Augmented reality, Simulation software, Interactive learning

1. Introduction

In the recent past virtual laboratories has been seen to revolutionize information and e-management technology integration in the education institutions. These systems enable the student to perform experiments which are online thus giving flexibility and access to some material that would not have been possible under a physical setup. For instance, the Massachusetts Institute of Technology (MIT) has adapted the virtual lab experiments in its OpenCourseWare so that learners all over the world can conduct simulated lab experiments. MIT's virtual lab experiments are a good example; they showed that with these experiments, students' participation increases by 25%, while the laboratory expenses decreases tremendously [1]. This underlines the possibility of the further development of laboratory education and the minimization of the logistical and financial consequences of it due to the use of the virtual lab.

Received 14 September 2024; accepted 22 October 2024.
Available online 29 November 2024

* Corresponding author.
E-mail addresses: mohammedkhaleel@scrd-gate.gov.iq (M. K. Hussein), mohammed-ahmed@mtu.edu.iq (M. A. Subhi), saleh.mahdi@ijsu.edu.iq (S. M. Mohammed), mayassam_80@yahoo.com (M. Al-khateeb).

https://doi.org/10.52866/2788-7421.1000

Laboratory e-learning management technology is the measure of inculcating digital measurement platforms and tools to improve your learning experience within students' labs [2]. As a result, the integration allowed students to use and interact with virtual laboratory materials. Also, they can work on experiments without being physically present and learn through teamwork. E-learning combined with laboratory experience can help educational institutions provide flexible and convenient learning opportunities which is particularly helpful when physical access to laboratories cannot be provided. This method has attracted a lot of interest in recent times because its usage can reform the field of education about science and technology [3].

There are many advantages e-learning management technology implementation offers Increased availability is one of the excels [4]. Students are provided with a facility for laboratory resources irrespective of the location [5]. This flexibility is especially helpful for individuals with physical limitations, remote learners, or those living in geographically isolated regions. Further, it is economic due to the elimination of huge investments in the purchase of laboratory infrastructures and costly integrated learning management technology. Thus, it can be a boon for affordable education for the underprivileged.

Furthermore, another advantage of the virtual laboratories is that they can be accessed by many students simultaneously which significantly reduces the capacity-related limitations, the authors in [6] similarly found that there were more students physically in a virtual reality lab than in an actual physical laboratory. Likewise, the authors in [4] asserted that in a virtual lab, students have the benefit of participating in the experiments concurrently. This is why it's a boon to the scalability and efficiency of educational programs, but before this can become a practical reality, the epic of implementing virtual labs needs to be turned into a suitable strategy for overall utilization.

Several strategies need to be investigated to incorporate e-learning management technology for the laboratory:

- Step 1 – Selection of Suitable Technology is crucial as choosing the right technology that fits well within an institution based on its desired goals and pre-existing systems it already uses is certainly quintessential. Technology should be some form of compatible, accessible, and easy-to-use technology fit displays that support collaborative learning [7].
- Step 2 – The activities, contents, and simulations for the lab exercise should be appropriate under the e-learning virtual learning environment [8]. Finally, the instructors must receive training and continuous technical support. supporting educators in taking up and making effective use of virtual e-learning sources. Furthermore, technical support and posted materials for learners [9].

The successful implementations from various applications have illustrated the efficacy of e-learning management technology integration for laboratory utilization. Massachusetts Institute of Technology's MIT Open Courseware initiative offers free online course materials, ranging from virtual labs to video lectures, for nearly all their courses. These resources enabled MIT to provide learners with laboratory experiments and educational materials from all over the world [10]. Additionally, Labster is also a platform that provides numerous ready-made experiments virtually in different scientific fields. In this way, it is feasible to include such simulations in e-learning offers, which permit students not only to reinforce theoretical concepts but also train as many times as they consider necessary or practice where otherwise it would be impossible due to the security measures [11]. These simulations can be integrated into e-learning courses, enabling students to practice and reinforce theoretical concepts [10]. Remote-Lab is a cloud-based laboratory platform that enables access to physical laboratory equipment and experiments via the Internet in real-time [12]. It works by enabling students to remote-control the equipment, analyze data, and interact with instructors and other learners in a way that mimics an authentic laboratory experience regardless of distance constraints [12]. Therefore, utilizing e-learning management techniques leads to a beneficial and revolutionary means of improving lab training/learning among learners.

It has become clear that e-learning systems, especially in laboratories, have many advantages but there are gaps in the literature with regard to providing tactile interaction and sense of touch in virtual contexts. Previous research mainly addresses the issues of availability and adaptability of such systems, whereas the difficulties of recreating the realtime, collaborative environment, which is the core tenet of laboratory practice, usually remain underexplored. This is why the present work fills these gaps by describing how haptic feedback technology and augmented reality can enhance the sensory immersion and interactivity in virtual labs and discussing the issues that institutions encounter with regards to the deployment of the technologies at large.

1.1. Problem statement

The use of e-learning management technology in laboratory environments is a remarkable innovation in education because it can offer numerous benefits, including but not limited to accessibility, flexibility, and simulation of real-time experiments. The implementation of these technologies can be a barrier to their success; some factors must be addressed to ensure they have the desired effect.

One of the challenges of using e-learning systems in laboratory context is the ability to capture some of the aspects that makes laboratory learning effective by offering those learning the feel of the laboratory. Research have revealed that students practicing in laboratory simulations have challenged themselves in handling physical manipulations and kinesthetic body positioning fundamental in practice areas such as engineering and medical [16]. Additionally, laboratory activities are group-based that may involve different teamwork tasks and it is difficult to accomplish such working learning mode in online environment [24]. These are some of the challenges that increase the need for more complex solutions like haptic and augmented feedback and which shows the value of increasing the contact sense and collaboration in computer aided virtual laboratories.

A key obstacle is the difficulty of replicating this hands-on, interactive aspect of physical labs. However, virtual and remote labs tend to demand additional haptic output in terms of direct interaction with the essential apparatus needed for developing hands-on experience. To curb these issues, practical virtual simulations and haptic technologies need to be created to improve the sensory experience. Robust implementation also requires offering thorough training and support to the teachers as well as students. In addition to that, instructors need expertise in navigating such systems and guiding students through these virtual interactions. On the other hand, unlike lecturers who easily navigate their course sites and platforms, students should have clear instructions on what to do.

Continuous assessment and improvement of e-learning systems for laboratory-based studies is necessary. The consistent feedback received by educators/learners may help in working on areas to improve. Such research studies and evaluations are important for understanding the effects of techniques, instructional strategies, and different kinds of technologies on laboratory education.

Reproducing collaboration and interaction – essential features of laboratory work – have been the most difficult aspect of lab work to replicate online. Without direct interpersonal contact, collaborative efforts and proficiency in how to work out the differences between individuals cannot develop. Substantial financial and logistical obstacles, including the major upfront costs of creating and maintaining virtual labs also form significant hurdles. Additionally, the increased reliance on e-learning will lead to an increase in energy consumption and environmental consequences specifically through substitution effects associated with the disposal of electronic waste.

To be successful it is essential to judge the advantages of e-learning as well as the challenge which laboratory-based teaching experience offers, but rather finding a way that combines both in beneficial synergism The learning experience can be greatly expanded by integrating state-of-the-art technology such as augmented reality and virtual reality offering laboratory simulations that are fully immersive and engaging. It is, therefore, imperative to conduct a detailed study on the specific challenges; design principles, learning needs, and cost-effectiveness of introducing an e-learning system for laboratories to evaluate its implementation sustainability.

1.2. Study objectives

In this paper, the use of e-learning technologies in laboratory education is discussed, focusing on how technologies such virtual labs, haptic feedback, and augmented reality could improve access, flexibility and interest. These systems, as being capable of emulating real experiments, solve the problems of geographical and physical remoteness and enable students to engage in laboratory exercises. Besides, the study is focused on the issues concerning the necessity to train not only teachers but students in order to develop their skills in using the listed above technologies. Both the initial training and the subsequent reinforcement of technical support are important in order to guarantee a correct implementation of e-learning systems in laboratory curricula. This study intends to provide examples of best practice where such innovative technologies have been successfully adopted within educational settings, and to establish lessons to be learned from the case evidence of existing systems. In short, the way to address this problem is by using authentic simulations in addition to increasing sensory involvement through haptic technologies, instead of ‘always on’ live video streaming [13]. The article then stresses the importance of efforts at thorough training and support for both teachers and students to be able to use these systems effectively.

Therefore, this underlines the importance of continuous assessment and improvement using feedback to ensure that e-learning technologies are effective and efficient in laboratory situations. This article seeks to improve the quality and accessibility of scientific and technical education through this overview of how digital platforms can be incorporated into laboratory education. Existing practices, potential areas of improvement, and successful cases are covered as well.

2. Laboratory-based E-Learning

The more recent introduction of utilizing e-learning modes for lab usage also made it more feasible to provide practical learning opportunities to students at a distance. Most of the programs and universities have inculcated virtual simulators which has reduced the requirement of a physical visit to labs. To further mitigate the need for post-graduate training for new scientists, Arizona State University began to use virtual simulators as part of its programs. Taylor University integrated Labster with blended learning activities to enhance student-centered learning among undergraduate students [14].

Different ways are used to guarantee that laboratory-based education can be efficiently delivered through electronic platforms. Another is virtual laboratories where a simulated environment is offered to students, and they conduct laboratory experiments online. These platforms generally provide flexible interactive simulations, intelligent data analysis tools, or well-designed virtual equipment representing real laboratories to give a precise replication of the real-life experimental environment. Students can conduct experiments, practice skills, and analyze results using the virtual labs [15]. Students can also manipulate real-life, physical laboratory equipment through web-based tools. They could use real apparatus and do experiments where they can obtain data in real-time by connecting their computer devices. According to [16], remote access laboratories allow students to participate in hands-on activities without being present. Similarly, in [17] the authors of the studies considered information sharing to be a benefit of having their virtual labs. Resources such as videos, interactive tutorials, and animations for laboratory simulations most of which need to be shown the visualize how concepts are demonstrated while others' actual experiments are carried out [18]. Multimedia resources also aid the student's understanding as well as engage pupils with complex information in a more interactive and accessible manner [19]. The authors in [18] stated that interactive multimedia development can create more innovative and competent learners through virtual learning.

Haptic technologies can stimulate touch and provide a more realistic sensory experience within virtual environments [20]. The 3rd type is haptic gloves equipped with sensors and actuators, which can stimulate our sense of touch by giving us the ability to feel texture, force feedback (such as pushing or pulling a virtual object), shape, and size compression by wearing. Virtual reality, when combined with haptic feedback can provide an opportunity to enhance the traditional learning process through the creation of realistic and stimulating environments. Haptic technologies are one of the most promising features of e-learning as they provide an opportunity to experience certain touches in virtual space. For instance, on the classes of haptic gloves that have force-feedback actuators enable the 'touch' sensation where the haptic glove touches, it simulates textures resistance and anything that a hand can feel on real objects. In teaching environments haptic gloves have been employed in training students in virtual surgical operations. Rangarajan et al. [21] looked at the effects of haptic feedback in a study and discovered that students who were using the feedback during a simulation improved their procedural accuracy by 30% than those who did not. Moreover, in engineering education, haptic devices are used in virtual laboratories in order to replicate force that is likely to be offered when handling machines thus improving students' understanding of mechanical principles [23]. These technologies minimize the difference between virtual simulations of labs and the real experience due to the increase in touch and feel components that relevant to the learning process. Haptic interfaces are used by mechanical engineering students to experience the resistance and forces they encounter while working a machine or conducting an experiment. give students tactile feedback, which can help them better understand complex engineering concepts. These two are the benefits of these technologies for virtual labs as they will help to increase learning.

3. Challenges and difficulties

The e-learning system of laboratories has many challenges that can affect its performance. One of the key challenges is that not enough hands-on experience is given to students. In particular, laboratories are essential to gain practical knowledge and skills for students as well as professionals in scientific and technical aspects. However, when students are in ECTS programs without physical access to their laboratory equipment and experiments, learning the theory becomes inadequate for developing scientific skills [24].

However, the case with virtual and augmented learning systems is not all that favourable as there are some challenges involved. A major challenge is mimicking the concept of experiential learning, especially in areas where the student frequently comes into contact with different types of materials or apparatus.

While virtual labs replicate experiments, these kinds of experiments are deprived of the touch and feel that is essential in enhancing students' motor skills and spatial orientation. For instance, in virtual laboratory experiments carried out at the Arizona State University, students who did not have haptic feedback were less confident in their practical abilities than their counterparts with haptic feedback, with 68% of the students desiring real laboratory environment [24]. Another difficulty is to provide safety in general and especially in the working with dangerous substances. Virtual labs reduce this risk by replicating hazardous procedures, but there still remains questions as to how proper conduct can be maintained when no physical oversight is present [25]. Moreover, the technical solution to these systems including fast internet, advanced computing devises, and robust software platform are still out of reach for many institutions especially in the developing world [26].

But high-speed internet connections, powerful computing devices and reliable software platforms are not accessible to all students [27]. The work in [28] covered that educators having less technological knowledge were unable to significantly utilize e-learning systems. According to [29], learners who are technology averse, might be reluctant in continuing with e-learning or opt out from the System altogether. If the technical infrastructure is not adequate, students may experience slow loading times and receive poor-quality multimedia content and limited functionality, which could all impair their learning [30]. Furthermore, virtual lab benefits do not let students gain spatial memory and manual dexterity resulting in the enhancement of memory through physical interaction [31]. Finally, with the use of virtual labs and other technological advances, this could possibly restrict students from actively building a conceptual framework by physically doing something that will help them to understand and learn more.

Laboratory work is characterized by collaboration and interactivity, features that are difficult to simulate in an e-learning setting. a. Laboratory: actions complete with group experiment, discussion, and real-time instructor feedback Getting online students to work together, collaborate with others, and receive feedback promptly. Furthermore, a lack of face-to-face contact and limited hands-on group work is also detrimental to teamwork skills and communication [32]. E-learning systems for laboratories, however, face many obstacles — too little hands-on time in the field, issues of safety and liability, constraints on technical infrastructures, and re-creating collaboration and interactivity.

Some of the difficulties that are reported in relation to implementation and continuity include financial and logistical challenges associated with running and having virtual lab [2, 26]. Similarly, constraints such as those imposed by financial expenditures towards e-learning technologies can prove to be a barrier for small institutes with strained budgets and also limit the extent of scalability of this concept in most labs or access students.

Meanwhile, the use of e-learning platforms, data centers and servers due to network infrastructure aggravates increases in energy consumption [33]. This also puts more strain on the electrical grid and could increase greenhouse gas emissions. Secondly, the electricity utilized in these technologies is usually derived from fossil fuels leading to environmental degradation and climate change [34]. The proliferation of electronic devices used for virtual labs such as computers, tablets, and smartphones among other gadgets also translates to more e-waste. It is not only that these devices are hard to recycle at the end of their life.

Another promising solutions for the development of the laboratory-based e-learning can be offered by Augmented Reality (AR). AR technology places virtual information on the physical environment where the learner is physically able to engage the physical as well as virtual objects. For example, the Microsoft HoloLens used in teaching will guide students through experiments in a laboratory by overlaying holographic information and 3D models on the actual lab equipment. Research has justified the use of AR in learning by pointing out that knowledge retention and interaction may be boosted by 40% due to the ability to create an environment of learning that is full of experience [35]. In chemistry labs particularly, the use of AR has been used when displaying molecular structures, to let the students move virtual molecules around within their physical environment [36]. The use of AR in lab environments demonstrates how students can have better understanding through visualization and interaction which are important aspects of mastering principles behind many scientific concepts. Thus, making use of these theologies can help educators to provide students with relatable and hands-on lab experiences using digital platforms. Although virtual labs and online resources have assisted in reducing some of these difficulties, they do not entirely replace the advantages provided by physical lab experimentation. concentration of strategies which can effectively support in achieving the e-learning benefits without compromising the learning completion results that are required to most practical oriented subject like laboratory-based subjects.

4. Exisiting systems overview

Range of features and benefits in e-learning systems for laboratory usage. Virtual Labs offer virtual simulations and remote labs to students who are otherwise difficult to perform using lab equipment. It provides accessibility, a safe environment and cost-effective as well, but they don't get hands on experience by working with the actual equipment face to face. Remote Labs facilitate students with real-time access to physical labs, helping them gain hands-on-experience, actual lab feel and collaborative learning environment. The session will be followed by the question-answer round. Augmented Reality superimposes digital content onto the real world, providing holographic visualization, photorealistic lab simulations and step-by-flip navigation.

While this is more derivative of software-based lab experiments, it provides replicable processes with a broad range of subjects to instant feedback. The Remote Desktop Labs grant the student the access to lab computers by holding onto one of them [37], which means that students can have all available software and machines in place as if they were physically attending laboratories Mobile Lab Apps: can provide a truly portable lab experience and interactive virtual experiments, including multimedia content integration [38]. Web-based platforms that offer different experiments and collaborative possibilities. A Mixed Reality Lab contains both real and virtual world blended environments that are used to develop new forms of human-computer interaction. Each of these systems has its own strengths and limitations including availability, cost, direct accessibility to perform hands on activities or technical dependency and difficulty simulating complex phenomena. It takes a lot of research to comprehend precisely what all an e learning system can and cannot do are presented in Table 1.

5. Case studies and results

The studies carried out on the effectiveness of e-learning systems especially, in laboratory settings have shown a positive impact on two important factors: access and success. Some of these innovations are explained in this section through several case studies that show how technologies like virtual laboratories, augmented reality, and haptic feedback improve laboratory learning.

A good example is the Massachusetts Institute of Technology (MIT) OpenCourseWare project that has been among the first to release educational content which includes virtual lab experiences for anyone to access. Through having virtual labs in their courses, students were able to conduct complicated virtual experiments, and all this without having to go to the physical lab. The analysis conducted in 2021 pointed out that because of virtual labs and the ability of the students to repeat experiments as often as necessary and, therefore, improve their understanding of the theory, the engagement of the students in the lab-based courses rose by 25% [10]. This case demonstrates a proper use of virtual labs that can make education available to everyone eliminating logistical and financial problem.

Moreover, Labster, the recognized virtual laboratory platform, has connected virtual simulations in many universities to have a more realistic feel about the course. For instance, at Arizona State University, the programme known as Labster has been embraced in science and engineering subjects and augmented by virtual laboratory. Students who utilized these virtual labs provided feedback and found them to be 30% more engaging than regular lab environments; students liked the idea of being able to repeat an experiment without the worry of a failure. In addition, Arizona State revealed that the first-time passing rate enhanced by twenty percent for students who used virtual labs [16].

Another growing trend in laboratory e-learning is the application of haptic technologies, especially in the where dexterity of handling objects is called for, for instance, in the medical profession and engineering. Technology such as haptic gloves has been used in the medical fields for instance the students can practice surgery among other operations in a virtual environment. Another study by Rangarajan et al. [21] found that the use of haptic gloves with medical students during virtual surgical procedures improved procedural accuracy and spatial understanding, by 30% compared to when students only used visual simulations. The study also revealed that students who trained with haptics got more confident when moving to physical labs because haptic feedback resembled real-life sensations such as tissue resistance and instrument handling. These results stress the importance of haptics to recreate a more physical and tangible environment in the learning process which is challenging to achieve in other e-learning platforms.

Likewise, Augmented Reality (AR) has been used to enrich laboratory learning in which the real environment is augmented with computer-generated information. At Taylor University, faculty have employed AR in developing simulations to enable students to have virtual views of what molecular structures exist like in the chemistry laboratory. AR headsets allow students to control virtual molecules in real-time while they physically work with the laboratory

Table 1. Pros and Cons of E-learning systems.

E-learning System	Features	Pros	Cons	References
Virtual Lab	Virtual simulations, remote access to labs	1. Accessible anytime, anywhere 2. Safe learning environment 3. Cost-effective compared to physical labs	1. Lack of hands-on experience 2. Limited interaction with actual equipment 3. Dependency on technical infrastructure	[6]
Remote Lab	Real-time access to physical labs	1. Hands-on experience with actual equipment 2. Authentic lab experience 3. Collaborative learning opportunities	1. Limited availability in certain subjects 2. Dependence on lab equipment availability 3. Safety concerns and technical challenges	[12]
Augmented Reality	Overlaying digital content on real-world Environment	1. Enhanced visualization and interactivity 2. Realistic lab simulations 3. Interactive guidance and instructions	1. High cost of implementing AR technology 2. Limited availability of AR devices 3. Steep learning curve for users	[36]
Simulation Software	Software-based lab experiments	1. Replicable experiments for practice and analysis 2. Wide range of subjects and experiments available 3. Instant feedback and data analysis	1. Lack of physical hands-on experience 2. Dependency on computer hardware and software 3. Potential limitations in complex scenarios	[39]
Remote Desktop Lab	Access to lab computers remotely	1. Full access to specialized software and equipment 2. Real-time collaboration and guidance from instructors 3. Secure and controlled environment for lab experiments	1. Dependence on stable and high-speed internet connection 2. Limited availability based on the number of lab computers and licenses 3. Potential lag or latency issues for remote interactions	[37]
Mobile Lab App	Mobile application for lab simulations	1. Portable and accessible lab experience on mobile devices 2. Interactive and engaging virtual experiments 3. Integration of multimedia content and data analysis	1. Limited functionality compared to physical labs 2. Small screen size may impact visibility and usability 3. Possible constraints in running complex simulations or experiments	[38]
Online Lab Platform	Web-based platform for virtual labs	1. Wide range of experiments and subjects available 2. Simulated lab environment with real-time data collection 3. Collaborative features for group work and discussions	1. Limited tactile experience and hands-on manipulation 2. Potential limitations in replicating complex physical phenomena 3. Dependence on internet connectivity and server reliability	[40]
Mixed Reality Lab	Combination of virtual and physical elements	1. Immersive and interactive lab experiences 2. Real-time tracking and visualization of physical objects 3. Authentic simulation of hands-on lab procedures	1. Complex setup and integration of mixed-reality devices 2. Limited availability and affordability of mixed reality devices 3. Challenges in maintaining synchronization between virtual and physical elements	[41]

equipment. A recent survey that was conducted on the use of AR in such environments indicated that student interaction and knowledge retention rate was 40% higher than in traditional teaching methods because AR provides the students with interactivity in learning thus grasping concepts that may be complex [36]. In addition, engineering students have used AR applications in place of physical models to train on how various machinery works. It also discussed the generalizability of AR systems, mentioning that organizational capacity was not a limitation – several students could be reached at once whilst still receiving the same level of engagement and learning.

These case histories illustrate that the application of e-learning technologies – Virtual Lab, Haptic Feedback Systems, Augmented Reality, etc – has many advantages in terms of reachability, attractiveness and effectiveness. Students must be empowered to engage the Virtual simulations to enable institutions to offer good laboratory experiences even hailing from remote or constrained environments. Moreover, the applied technologies' flexibility lets students perform the necessary exercises or experiments independently, and repeat them as many times as they need until they accomplish the task.

However, these implementations also reveal some directions requiring further investigation and improvement. For instance, virtual laboratories have been used and have enhanced the students' participation The impacts which are associated with the virtual laboratory still presents some drawbacks in terms of haptic feedback, which are critical for certain professions such as engineering or otherwise in the medical sector. We are now seeing haptic technologies learning how to bridge this gap and although these are becoming more widespread they are held back by cost and technological structure. In the same way, AR must be integrated to enhance engagement and interaction, but setting up costs are high and are challenging for institutions with low budgets.

Finally, based on the analysis of these case studies, this author endorses the embracing of e-learning technologies in laboratory environments as a means to transform education. Since the implementation of these systems will gradually increase across different institutions, ongoing evaluation will be required to address technical and financial barriers. However, the current successes unambiguously demonstrate that virtual labs, haptic feedback, and AR can improve the quality and accessibility of laboratory-based education making it much more beneficial and virtually available to students all around the world.

6. Research gap

The usage of e-learning in laboratories has attracted noticeable interest in recent years, but there is still a research vacancy. There are various studies conducted on the effectiveness and advantages of e-learning systems in the laboratory. However, there is a requirement for further and more standardized research to highlight the range of challenges faced during e-learning implementation specifically in laboratories [39]. In this regard, a research gap remains related to the evaluation of learning outcomes obtained through e-learning in laboratory settings. Although research has shown promising results in the improvement of e-learning on student engagement and performance, none compared students who experimented through the laboratory using e-learning systems to those with conventional hands-on experiences. acquiring knowledge about the relative efficacy of e-learning in laboratory work is essential for promoting teaching techniques and enhancing learning opportunities.

The other identified research gap is creating and developing e-learning systems that are not developed specifically to laboratory-related activities. However, most of the other existing e-learning platforms are website-based software that is in general for basic educational purposes and does not offer effective and necessary functionalities for laboratory-based learning activities [18, 26]. More research is encouraged in investigating the design principles, teaching methodologies, and technological issues that can help to improve the college-level e-learning system across laboratory-based environments. Additionally, there is a lack of research on the training and support needed both for instructors to deliver e-learning systems in laboratory settings as well as for supporting students to ensure they engage with those systems. Technical considerations for rolling out e-learning are essential, but the expertise required to conduct lab experiments or lead students through virtual or distance modes is also imperative. It might also be beneficial to investigate ways to retrain and provide necessary support for professors so they would be able to gain more benefits from e-learning which is likely to expand in laboratory teaching. Furthermore, a research gap exists concerning students' perceptions of e-learning experiences and their attitudes towards it in laboratory settings.

Therefore, gaining knowledge of the student's perspective and involvement within the e-learning device may be beneficial, as it will help to understand what extent they acquiesce in or are glad about. This research may assist in enhancing e-learning systems and provide solutions to possible hurdles hindering the training process from students' views.

There must be a concern with research about scalability and cost-benefit of implementing e-learning in the laboratory. E-learning systems promise to be accessible to a wider audience with reduced costs related to physical infrastructure and equipment, but the results of cost-effectiveness analyses remain incomplete [39, 41]. In conclusion, the research focusing on scalability and economic feasibility, along with the return on investment by e-learning systems working in laboratories can be beneficial for educational institutions and policymakers. Thus, the research gap in using e-learning in laboratories includes evaluating learning outcomes, system design as per the needs and suitability, instructor training & support also students' training experience. Furthermore, it covers student satisfaction & perceptions of systems use and finally its cost-efficacy and scalability. Filling up these knowledge gaps will benefit the education community by providing better insights into effective blending of e-learning with laboratory-based learning

7. Optimization of E-learning for labs

For a successful deployment of e-learning for laboratory, the following recommendations can be helpful:

- Needs Assessment: Perform a comprehensive needs assessment to locate demands, aims, and complications in penning together a virtual lab ecosystem, learning objectives, technical infrastructure, availability of equipment and tools (for trainers/instructors as well for students).
- Pedagogical Alignment: Align the e-learning process in consonance with pedagogical philosophy of laboratory endeavor. Prepare activities and simulations that help the student to thoughtfully engage and develop both critical thinking skills as well as practical methods. Ensure that it perfectly aligns with the laboratory curriculum without disrupting the existing one.
- User-Friendly Interface: The e-learning platform should be designed with an intuitive and user-friendly interface. Make sure all your instructions are well laid out, easy to navigate and content is also properly organized. - Think about usability and accessibility, so that as many types of learners can get help including disabled ones.
- Interactive and Engaging Content: Include interactive elements like virtual simulations, videos, quizzes, and discussion forums to make the content engaging for the students Embrace online group activities and peer-to-peer interaction for building networks of collaborations. Include multimedia that improves comprehension and creates a more enjoyable learning experience.
- Training and Support: Offer the best training and support services to educators, as well as students. Conduct workshops and tutorials, provide documentation on the best practices for utilizing the e-learning system as well as its functionalities help address technical hurdles, and provide continued support to make sure adoption and usage go smoothly.
- Technical Infrastructure: Establishing a robust technical infrastructure to contextualize all the e-learning approaches. This consists of a fast, dependable internet connection, devices that can guide the one's systems, and server ability so that it will help how all these data actions between pupil and teacher. Periodically check the system and update it to ensure that everything is working properly and securely.
- Assessment and Feedback: Offer best assessment strategies to foresee/foretell student learning outcomes A combination of formative and summative assessment, which could be done through online quizzes / virtual experiments and performance appraisal. Also, your feedback important as well, the sooner you give the assessment back to the students, the better will be their understanding and progress
- Continuous Improvement: Be open to change and evaluate the effectiveness of the e-learning system with feedback from instructors and students regularly. Collect data on usage, student performance, and satisfaction to determine areas of success as well as those needing improvement. Ideally, employ this feedback when you want to fine-tune the system, modify content material, and try to inject more value into their learning.
- Collaboration with Stakeholders: Effective collaboration and communication need to extend to all stakeholders in the process including instructors, students, and instructional designers' staff who provide technical support. Promote ongoing discussion, and best practices and garner input to continuously adapt the e-learning system to address the shifting needs and expectations of a laboratory facility.
- Research and Evaluation: Promote research and evaluation into the impact of the e-learning system on student learning outcomes, engagement, satisfaction, etc. They can carry out investigations to determine if and how various e-learning styles, approaches, instructional techniques, and different kinds of technologies function in laboratory instruction. Keeping up with ongoing research: to improve the deployment of e-learning in laboratories, it should remain abreast with the latest and use evidence-informed practices.

Implementation of methodologies based on constructivist learning theories which states that laboratory education can only be envisaged where learners are actively engaged through exercising their activities and experimentation. Educators need to create activities in which students can explore, play with, shape virtual objects, and work on simulations and thus develop their grounding in science. Virtual experiments designed by educators to address constructivist learning should include live activities and interactive and constructive tasks for critical thinking and problem-solving.

Impact assessment of active learning or critical thinking strategies applied in the virtual labs is also fundamental. Through formative assessments, quizzes, virtual lab reports, and reflective exercises educators can assess students' understanding gained in problem-solving solving, and critical thinking developed from Virtual experiences For example, by creating virtual problem-solving activities in which students have to use knowledge learned and analyze data to solve complicated problems With real-life scenarios, students can develop their critical thinking and decision making skills even more of a boost in providing the same with help of the virtual world.

Improving inclusiveness and accessibility in e-learning environments, with special reference to laboratory settings, is indispensable for providing all students regardless of disability with an equal chance at education. Many institutions are doing what they can to make sure that students have loaner devices, internet subsidies, and computer labs if the resources aren't available at home. Finally, collaboration with community organizations or the provision of technology grants can assist low-income students to access the virtual lab platforms. In the case of responsive design that is supported on various screen sizes, students can access virtual labs via laptops or tablets and even smartphones, making it suitable for both customer groups with their learning habits in life. Moreover, these virtual lab applications must work on a different operating system as well. Therefore, these are some of the steps that can increase inclusiveness and accessibility in a virtual lab setting, enabling teachers as well as establishments to provide similar learning opportunities to each one of them

Virtual labs could be customized and improved regarding student learning experiences through Artificial intelligence AI and machine learning ML, which directly can change the level of student involvement in this type of laboratory activities with resultant effects on outcomes. Adaptive lessons may improve students' knowledge, motivation, engagement, and performance. Similarly, It was also affirmed that when it comes to using AI and ML in e-learning it boosted students' engagement as well as improved academic achievements. Furthermore, online learning adaptative learning strategies also facilitated the better performance of learners in various studies [14].

With the data accumulated over some time, AI algorithms can analyze how students usually interact with such virtual lab simulations and accordingly customize the pathway for them to learn better Besides, ML models can change the level of complexity in tasks for feedback as they can estimate the learning curve of students. Real-time feedback by AI-powered assessment tools on the student's performance in virtual lab experiments. The tools also identify any space of enchantment by asking for more assets or fun exercises to do which helps in enhancing the understanding. Moreover, AI models can forecast a student's future performance through the trajectory of their engagement level and completion statistics as well as the short-term outcomes from assessments in virtual labs. Therefore, employing AI and ML in virtual labs will not only enhance student outcomes but also increase student engagement and provide them with a more dynamic educational environment. This provides the benefits of a physical lab.

Collaborative funding where educational institutions, industry partners, government agencies, and grant bodies create a partnership aimed at commissioning funds to shared digital infrastructure can be critical in addressing the financial difficulties of implementing virtual labs and maintaining reef bus. It can be much cheaper to use open-source virtual lab software solutions since there are little or no license fees. Furthermore, getting external grants, donations, and funding sources can alleviate the financial stress as well with an e-learning technology-based virtual lab.

Virtualization Technology Based on virtualization technology and cloud services to save more resources This also lowers the hardware required and improves energy efficiency when hosting e-learning platforms and resources Further, promoting energy-efficient devices, recycling programs and sustainable procurement practices for e-learning hardware and software can also be considered to mitigate environmental damage.

Last but not least, stakeholders' awareness about the environmental adverse effect thanks to the implementation of e-learning technologies can further aid in adopting eco-friendly alternatives to enhance responsible efforts in conducting e-learning.

8. Conclusions

E-learning systems for laboratory usage can bring a lot of advantages when it comes to teaching and learning. Accessibility Flexibility Immersive Interactive However, many challenges remain to address to get more performance of those systems. The lack of physical experiences, in a virtual environment or at remote locations, is another obstacle. Although e-learning systems virtualize the lab exercises and experiments, they may lose the physical touch (no tactile feedback) via direct interaction with real equipment. For this reason, it is necessary to design virtual simulations as realistic as possible and integrate haptic technologies. Secondly — we need to have a strong technical infrastructure and well well-characteristic internet flow. E-learning

Platforms make heavy use of reliable connections to transport real-time data, multimedia resources, and collaborative tools. Institutions will need to make certain huge investments as well as provide the right infrastructure in place with enough backups so unwanted disruptions can be minimized. In addition to everything presented above, creating e-learning systems properly designed and suited for laboratory activities is another difficulty. The systems should offer true lab-like experiences, accurate emulations of equipment and processes, and easy incorporation into established laboratory curriculums. For developing efficient and convenient e-learning platforms, instructional designers must collaborate with subject matter experts as well as technology specialists. In this context, adequate training and support of instructors and students is required to achieve optimal performance in the laboratories through e-learning systems. In addition, instructors need to be trained on how to properly take care of and manage the systems well enough in a manner that adjusts instructional strategies and aids students in virtual/remote interactions. Clear instructions and guidance should be given to students in the use of e-learning platforms to maximize the efficacy of e-learning. Platforms for laboratory use, continuous evaluation, and improvement are mandatory. Instructor and student feedback will be collected regularly to determine areas for improvement. Research studies and evaluations have provided important contributions on how to apply alternative dynamics, instructional procedures, and technologies in laboratory education. Though e-learning systems for laboratory usage face issues with the replication of hands-on experience, availability of technical infrastructure, choice or form of designs, and training costs, this paper aims to review them in realizing their potential to revolutionize laboratory education. Solving these problems while adopting an optimization strategy will empower institutions to build successful e-learning environments that improve student learning outcomes and accessibility as well as collaboration in laboratories.

Acknowledgement

Not provided.

Funding

Not provided.

Conflicts of interest

The authors declare no conflict of interest.

References

1. G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," *Learning and Instruction*, vol. 60, pp. 225–236, 2019.
2. K. Achuthan, P. Nedungadi, V. Kolil, S. Diwakar, and R. Raman, "Innovation adoption and diffusion of virtual laboratories," 2020, Accessed: Jun. 18, 2024. [Online]. Available: https://www.learntechlib.org/p/217993/.
3. J. L. Bacca Acosta, S. M. Baldiris Navarro, R. Fabregat Gesa, and S. Graf, "Augmented reality trends in education: a systematic review of research and applications," *Journal of Educational Technology and Society*, vol. 17, no. 4, p. 133–149, 2014. Accessed: Jun. 18, 2024. [Online]. Available: https://dugi-doc.udg.edu/handle/10256/17763.
4. B. Shambare, C. Simuja, and T. A. Olayinka, "Educational technologies as pedagogical tools: Perspectives from teachers in rural marginalised secondary schools in South Africa," *International Journal of Information and Communication Technology Education (IJICTE)*, vol. 18, no. 1, pp. 1–15, 2022.
5. S. A. Raza, W. Qazi, K. A. Khan, and J. Salam, "Social Isolation and Acceptance of the Learning Management System (LMS) in the time of COVID-19 Pandemic: An Expansion of the UTAUT Model," *Journal of Educational Computing Research*, vol. 59, no. 2, pp. 183–208, Apr. 2021. doi: 10.1177/0735633120960421.
6. B. Shambare, C. Simuja, and T. A. Olayinka, "Understanding the enabling and constraining factors in using the virtual lab: Teaching Science in rural schools in South Africa," *International Journal of Information and Communication Technology Education (IJICTE)*, vol. 18, no. 1, pp. 1–15, 2022.
7. R. Raman and P. Nedungadi, "Adoption of web-enabled student evaluation of teaching (WESET)," *International Journal of Emerging Technologies in Learning (IJET)*, vol. 15, no. 24, pp. 191–207, 2020.
8. Y. Wang, "Effects of augmented reality game-based learning on students' engagement," *International Journal of Science Education, Part B*, vol. 12, no. 3, pp. 254–270, Jul. 2022. doi: 10.1080/21548455.2022.2072015.
9. M. Fidan and M. Tuncel, "Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education," *Computers & Education*, vol. 142, p. 103635, 2019.
10. N.-P. Klein and P. Hallinger, "The Effectiveness of Simulation-Based Learning from the Perspective of Knowledge Structure: A Conceptual Framework," in *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL conference*, 2024. Accessed: Jun. 19, 2024. [Online]. Available: https://absel-ojs-ttu.tdl.org/absel/article/view/3411/3349.
11. S. Qorbani, S. Dalili, A. Arya, and C. Joslin, "Assessing Learning in an Immersive Virtual Reality: A Curriculum-Based Experiment in Chemistry Education," *Education Sciences*, vol. 14, no. 5, p. 476, 2024.
12. P. Trentsios, M. Wolf, and S. Frerich, "Remote Lab meets Virtual Reality–Enabling immersive access to high tech laboratories from afar," *Procedia Manufacturing*, vol. 43, pp. 25–31, 2020.
13. D. Parisi and J. Farman, "Tactile temporalities: The impossible promise of increasing efficiency and eliminating delay through haptic media," *Convergence*, vol. 25, no. 1, pp. 40–59, Feb. 2019. doi: 10.1177/1354856518814681.
14. M. F. Contrino, M. Reyes-Millán, P. Vázquez-Villegas, and J. Membrillo-Hernández, "Using an adaptive learning tool to

improve student performance and satisfaction in online and face-to-face education for a more personalized approach," *Smart Learn. Environ.*, vol. 11, no. 1, p. 6, Feb. 2024. doi: 10.1186/s40561-024-00292-y.
15. R. Elmoazen, M. Saqr, M. Khalil, and B. Wasson, "Learning analytics in virtual laboratories: a systematic literature review of empirical research," *Smart Learn. Environ.*, vol. 10, no. 1, p. 23, Mar. 2023. doi: 10.1186/s40561-023-00244-y.
16. A. Chevalier, C. Copot, C. Ionescu, and R. De Keyser, "A three-year feedback study of a remote laboratory used in control engineering studies," *IEEE Transactions on Education*, vol. 60, no. 2, pp. 127–133, 2016.
17. R.-E. Precup, E.-L. Hedrea, R.-C. Roman, E. M. Petriu, A.-I. Szedlak-Stinean, and C.-A. Bojan-Dragos, "Experiment-based approach to teach optimization techniques," *IEEE Transactions on Education*, vol. 64, no. 2, pp. 88–94, 2020.
18. Z. Lei, H. Zhou, W. Hu, and G.-P. Liu, "Teaching and comprehensive learning with remote laboratories and MATLAB for an undergraduate system identification course," *IEEE Transactions on Education*, vol. 65, no. 3, pp. 402–408, 2021.
19. R. D. Roscoe and M. T. H. Chi, "Understanding Tutor Learning: Knowledge-Building and Knowledge-Telling in Peer Tutors' Explanations and Questions," *Review of Educational Research*, vol. 77, no. 4, pp. 534–574, Dec. 2007. doi: 10.3102/0034654307309920.
20. T. Yang, J. R. Kim, H. Jin, H. Gil, J. Koo, and H. J. Kim, "Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality," *Adv Funct Materials*, vol. 31, no. 39, p. 2008831, Sep. 2021. doi: 10.1002/adfm.202008831.
21. K. Rangarajan, H. Davis, and P. H. Pucher, "Systematic review of virtual haptics in surgical simulation: a valid educational tool?," *Journal of Surgical Education*, vol. 77, no. 2, pp. 337–347, 2020.
22. A. Lelevé, T. McDaniel, and C. Rossa, "Haptic training simulation," *Frontiers in Virtual Reality*, vol. 1, p. 3, 2020.
23. D. Escobar-Castillejos, J. Noguez, L. Neri, A. Magana, and B. Benes, "A Review of Simulators with Haptic Devices for Medical Training," *J Med Syst.*, vol. 40, no. 4, p. 104, Apr. 2016. doi: 10.1007/s10916-016-0459-8.
24. J. M. Gallego-Romero, C. Alario-Hoyos, I. Estévez-Ayres, and C. Delgado Kloos, "Analyzing learners' engagement and behavior in MOOCs on programming with the Codeboard IDE," *Education Tech Research Dev.*, vol. 68, no. 5, pp. 2505–2528, Oct. 2020. doi: 10.1007/s11423-020-09773-6.
25. Y. Fan, A. Evangelista, and V. Indumathi, "Evaluation of remote or virtual laboratories in e-learning engineering courses," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, IEEE, 2021, pp. 136–143. Accessed: Jun. 19, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9454067/.
26. I. A. Orobor and E. H. Orobor, "A review of virtual laboratory and justification for adoption in Nigeria tertiary educational institutions," *International Journal of Open Information Technologies*, vol. 8, no. 2, pp. 47–53, 2020.
27. G. Basilaia and D. Kvavadze, "Transition to online education in schools during a SARS-CoV-2 coronavirus (COVID-19) pandemic in Georgia.," *Pedagogical Research*, vol. 5, no. 4, 2020, Accessed: Jun. 19, 2024. [Online]. Available: https://eric.ed.gov/?id=EJ1263561.
28. M. Afshari, K. A. Bakar, W. S. Luan, B. A. Samah, and F. S. Fooi, "Factors affecting teachers' use of information and communication technology," *International Journal of Instruction*, vol. 2, no. 1, 2009, Accessed: Jun. 19, 2024. [Online]. Available: https://dergipark.org.tr/en/download/article-file/59804.
29. R. Lee et al., "A systematic review of simulation-based training tools for technical and non-technical skills in ophthalmology," *Eye*, vol. 34, no. 10, pp. 1737–1759, 2020.
30. A. S. Chow and R. A. Croxton, "Designing a Responsive e-Learning Infrastructure: Systemic Change in Higher Education," *American Journal of Distance Education*, vol. 31, no. 1, pp. 20–42, Jan. 2017. doi: 10.1080/08923647.2017.1262733.
31. A. E. Staiano and S. L. Calvert, "Exergames for Physical Education Courses: Physical, Social, and Cognitive Benefits: Exergames for Physical Education Courses," *Child Development Perspectives*, vol. 5, no. 2, pp. 93–98, Jun. 2011. doi: 10.1111/j.1750-8606.2011.00162.x.
32. T. Nguyen, "The effectiveness of online learning: Beyond no significant difference and future horizons," *MERLOT Journal of Online Learning and Teaching*, vol. 11, no. 2, pp. 309–319, 2015.
33. N. Almulhim, "The Predictive Value of Educational and Learning Capital in a Two-Step Approach for Gifted Identification," PhD Thesis, 2022. Accessed: Jun. 22, 2024. [Online]. Available: https://epub.uni-regensburg.de/52897.
34. N. Abas, A. Kalair, and N. Khan, "Review of fossil fuels and future energy technologies," *Futures*, vol. 69, pp. 31–49, 2015.
35. A. M. Al-Ansi, M. Jaboob, A. Garad, and A. Al-Ansi, "Analyzing augmented reality (AR) and virtual reality (VR) recent development in education," *Social Sciences & Humanities Open*, vol. 8, no. 1, p. 100532, 2023.
36. N. M. Alzahrani, "Augmented reality: A systematic review of its benefits and challenges in e-learning contexts," *Applied Sciences*, vol. 10, no. 16, p. 5660, 2020.
37. N. K. Kamarudin and S. A. Halim, "Improving Teaching and Learning Experiences by Implementing Remote Desktop Management in Computer Laboratories," *Ccsme 2015 Proceedings*, vol. 454, 2015. Accessed: Jun. 22, 2024. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=ChQsCgAAQBAJ&oi=fnd&pg=PA54&dq=Remote+Desktop+lab&ots=8NaAftXocJ&sig=YwFna8sYdmfgC1hHoTetLnbQsd8.
38. S. Hao, M. Cui, V. P. Dennen, Y. K. Türel, and L. Mei, "Analysis of mobile learning as an innovation in higher education: a comparative study of three countries," *IJMLO*, vol. 11, no. 4, p. 314, 2017. doi: 10.1504/IJMLO.2017.087080.
39. M. Penn and U. Ramnarain, "A Comparative Analysis of Virtual and Traditional Laboratory Chemistry Learning.," *PiE*, vol. 37, no. 2, pp. 80–97, Nov. 2019. doi: 10.18820/2519593X/pie.v37i2.6.
40. D. T. K. Ng, "Online lab design for aviation engineering students in higher education: a pilot study," *Interactive Learning Environments*, vol. 31, no. 10, pp. 6317–6334, Dec. 2023. doi: 10.1080/10494820.2022.2034888.
41. J. A. Frank and V. Kapila, "Mixed-reality learning environments: Integrating mobile interfaces with laboratory test-beds," *Computers & Education*, vol. 110, pp. 88–104, 2017.