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Education Without Walls: The Promise of Virtual Labs in the Teaching Process

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Abstract

Virtual labs are digital spaces that overcome the physical limitations of traditional classrooms. They employ simulation to foster real-time collaboration. Through these virtual platforms, the ways students address and understand theoretical concepts are transformed. In addition to concepts and principles, virtual labs help students develop fundamental professional skills, such as problem solving, application design, and error detection. Therefore, this study conducted a literature review to analyze virtual labs' potential to offer an education that is more accessible, dynamic, and interactive by foreseeing major changes in teaching processes. Virtual labs were found to represent a necessary and promising revolution within the field of higher education. Their implementation reflects not only the process of adaptation to a world undergoing constant technological changes but also the current and future needs of a varied and globalized student population.

Keywords: *Virtual Laboratory, Education, Teaching and Learning Strategies, Laboratory Practice.*

Introduction

In the digital age, education has undergone a major transformation to overcome the physical limitations of traditional classrooms. A new educational paradigm has emerged in the form of virtual labs, which are essential tools gaining increasing importance in the fields of teaching and learning. These platforms have been made possible through advances in pedagogy and information and communication technology (ICT) (Allen & Seaman, 2008).

Virtual labs have transformed teaching's traditional structure, enabling not only the imitation of reality (Gutiérrez, Rodríguez, & Herráez, 2018) but also the use of expensive, fragile, and limited tools. Thus, students can explore scientific, technological, and academic concepts in these labs. When the barriers present in physical learning spaces are removed, students have more flexibility, accessibility, and varied educational experiences, thereby allowing them to acquire knowledge more easily (Villalba, Moraleda, & Bencomo, 2008), (Guzmán, López B., & Torres, 2014).

Notably, the teaching–learning processes face some academic challenges, which are mainly related to the use of methodologies that enable students to develop skills for achieving greater autonomy in analysis, experimentation, and decision-making. Therefore, virtual labs become a supportive tool for fostering knowledge using teaching tools that enable an interactive and constructive environment (Infante, 2014).

Two key benefits distinguish virtual labs from physical ones. First, access to virtual labs has no time, schedule, or resource constraints. Thus, the use of expensive, fragile, and reactive materials is unnecessary, thereby improving student safety (Zaldivar, 2019), (Ruíz A., Moreno, & Arias M., 2011). Second, virtual labs help students develop skills and competencies based on theoretical knowledge and strengthen personalized learning processes, enabling students to learn at their own pace and explore scenarios in greater depth (Rodríguez, 2020).

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Therefore, this study aimed to analyze the potential of virtual labs to offer an education that is more accessible, dynamic, and interactive by foreseeing major changes in teaching processes. To do so, a literature review was conducted that focused on how virtual labs have transformed and continue to redefine education, thereby determining their impact on learning and their potential.

State of the Art

To obtain evidence of the implementation of these labs and their progress in cross-sectional areas, this study consulted seven databases. Articles on practices regarding the use of simulators and labs in universities specialized in engineering, health, and education were gathered.

In one study (Conde, Sanchez, Rico, Frias, & Romero, 2019), a virtual physics lab was created to teach electrical circuits using a crocodile simulator. Students obtained high grades through this implementation. Another study implemented a virtual lab designed in Unity to teach electromagnetism using an avatar (Castro, Flores, & Acosta, 2022). Through various interactive exercises, students were able to recognize important topics and achieved impressive results based on the concepts they had learned.

Another study designed a teaching prototype for calculations in the cloud to compensate for the hardware limitations faced by students (Gallardo, Razón, & León, 2020) . This prototype was achieved by using a virtual lab to conduct practical work with the PDIOO (Plan, Design, Implement, Operate, and Optimize) methodology suggested by Cisco Systems. The purpose was to strengthen training in engineering by enabling flexible learning through interaction, teamwork, and new technologies.

Furthermore, researchers built a virtual electronics lab to assess the effectiveness of basic practical electronics lessons in an extended classroom using the LTspice simulator (Navarria, 2023). Favorable results were achieved by both individual students and pairs. Similarly, another study designed a virtual kinematics lab using the mathematics application GeoGebra (Gañan, 2020), wherein they specified the problems faced in addressing kinematics learning with traditional methodologies and compared them with the advantages of using open educational resources that enable students to interact with simulators. The study identified the variables to consider when practicing different sports and made important progress in terms of the concepts, conversions, and understanding of the topic.

Additionally, (Catalán, 2014) evinced the importance of virtual labs by creating the open-source platform GridLabUPM, which manages 3D virtual worlds. Using this platform, students explore various scenarios and conduct virtual practices while interacting with other users and scenarios. This study also presented eLab3D, a remote laboratory for electronics, which allows students to simulate a real lab. Moreover, it presented the Risk Control Virtual Lab, which is used to experiment with meteorological conditions in crops, and the Sciences and Engineering Lab, which is used to handle materials used in physics in a real environment.

The PhET project (Cox, González, Magreñán, & Orcos, 2022), developed at the University of Colorado, offers various interactive virtual labs for different science and math subjects. These simulators are easily accessible open-source platforms that enable students to learn from scientific phenomena through exploration.

In addition, the authors of (Quitian Cruz, 2021) conducted a literature review of the problems found in microbiology teaching and compared traditional and virtual environments. Based on their findings, they suggested that virtual labs be used as a teaching strategy for fostering ICT in teaching–learning processes. Similarly, the authors of (Bonilla Trujillo, Villamil Reyes, & Montes Mora, 2019) demonstrated the advantages of teaching strategies that foster learning using educational tools to potentially impact individual and collective skills based on interactions with virtual labs.

Furthermore, the authors of (Triana Ortiz, Herrera Muñoz, & Mesa Mendoza, 2020) demonstrated the importance and advantages of using virtual labs in higher education compared with using on-site labs. To

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do so, they conducted a literature review and debated the key aspects of the effectiveness of using these labs in virtual higher education.

According to the aforementioned studies, there is a promising outlook to the debate regarding the use of virtual labs as a tool for enabling interaction in and the imitation of different work conditions of a real lab through simulators. For example, virtual labs enable teachers to reinforce the digital skills demanded of today's workforce.

Methodology

TABLE I. Databases Consulted for the Literature Review

Database	References
Proquest	10
Springer	11
Scopus	18
Web of Science	3
Scielo	9
Dialnet	11
Google Scholar	8
Total	69

The main search criteria were based on the applicability of virtual labs, safety, and teaching methodologies based on simulation and learning results.

This study conducted a literature review that analyzed the potential of implementing various virtual teaching tools. It was based on a search across seven databases for studies that have provided evidence for the use of these labs and the progress that has been made. First, various databases were consulted, which enabled the ideas of different authors to be identified to support the potential of virtual labs (Table 1).

Results

The findings of the literature review revealed the different views of authors regarding the promise of using virtual labs. It also revealed the progress made in their use through different knowledge areas, which has resulted in significant growth in curricular activities.

Since 1960, the goal of adding labs to curricula has evolved from enabling students to learn through discovery to something more constructive (Macas, 2024). According to (Reyes, Reyes, & Pérez, 2016), the use of labs has enabled a wider and more detailed understanding of subjects, where experiments play a crucial role through enabling visual and tactile methods. The appearance of virtual labs—real-time digital tools that do not require physical infrastructure—has made it easier for students to understand concepts and phenomena, thereby improving practical learning results (Infante, 2014).

In teaching and learning, universal challenges are faced by both students and teachers. The traditional distinction between theoretical and practical content has caused a lack of interest, low motivation, and poor performance, especially in areas where practice is essential (e.g., medicine). Teachers face a major challenge in the use of these tools (Lorca Marín, Cuenca López, Vázquez Bernal, & Lorca Marín, 2016), (Percepciones del profesorado ante el uso de simuladores virtuales en el aula de ciencias, 2023), which highlights the need to create environments for not only transferring knowledge but also fostering autonomous work, building knowledge, and applicability (Rodríguez Izquierdo, 2018); thus, learning through discovery can be explored in contrast to constructive learning (Velez & Erazo, 2022).

According to (Gato A. & Gutiérrez, 2019), virtual learning has emerged as a viable solution to the financial and resource-related problems faced by many universities, especially with the proliferation of the Internet

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(Iriarte-Solis, 2010). This e-learning model enables wider access to knowledge. Virtual and remote labs are commonly used by teachers as they enable students to interact with physical systems without the need to actually be present. Likewise, these labs have become a tool for supporting various research activities, including seedbeds and graduation projects, enabling students to develop skills related to inquiry and understanding (Benavides Martínez & Torres Escobar, 2024).

Potential of Virtual Labs

The scientific literature supports the development and use of virtual labs, focusing on the replacement of real environments with remote ones. A virtual lab's key quality is that it simulates a safe reality that enables interaction and the strengthening of learning processes. These labs thus provide a practical experience in an environment in which students can feel comfortable and less afraid of making mistakes (Orsega, Leonard, Ruggiero, Amato, & O´Hara, 2023), (Canónico, González, & Flores, 2024).

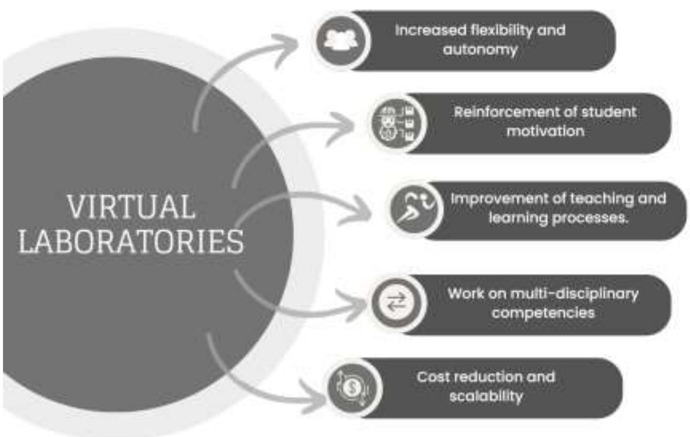
Therefore, one can infer that these labs enable the reinforcement of key concepts in academic training (Perez, DESARROLLO DE LABORATORIOS VIRTUALES EN INGENIERÍACON PARTICIPACIÓN DE ESTUDIANTES DE PREGRADO, 2022), (Cabrera Coronel, Centurión, & Mora Rojas, 2022). The experimental aspect helps students move from observation to variable handling and hypothesis verification, ensuring a rigorous process for students to build knowledge and develop the ability to interpret information (Asencios T., y otros, 2024).

The development of students' skills has been seen as a learning resource that provides flexibility and autonomy during learning and puts knowledge into practice, resulting in the acquisition of skills and abilities (González-Sorribes & Armesto-Ángel, 2023), (Velez & Erazo, 2022), (Perez, DESARROLLO DE PRÁCTICAS VIRTUALES PARA LABORATORIOS DE INGENIERÍA UTILIZANDO HERRAMIENTAS DE SIMULACIÓN, 2022), (Sáiz-Manzanares, Casanova, Lencastre, Almeida, & Martín-Antón, 2022). Thus, virtual labs are effective as long as they provide an answer to teaching demands and enable flexibility in knowledge acquisition.

The use of ICT improves the development of competencies, creates new elements and tools in teaching–learning processes (Carreño H, Ortega C, Simanca H, Blanco G, & Diago O, 2021), and generates interest in transforming said processes (Aguilar & Ayala, 2020). Nevertheless, one should consider these labs as a means to support teaching rather than an end (Espinoza Castro, Apolo Buenaño, Sánchez Barrera, & Bravo Guzhñay, 2024), especially in relation to the acquisition of skills related to students' achievements and the generation of procedural skills (Zúñiga, Jalón, & Albarracín, 2019).

Fig. 1 presents the contributions of virtual labs during teaching–learning processes, which provide evidence for the advantages of their use and applicability:

FIGURE I. Contributions of Virtual Labs to Education



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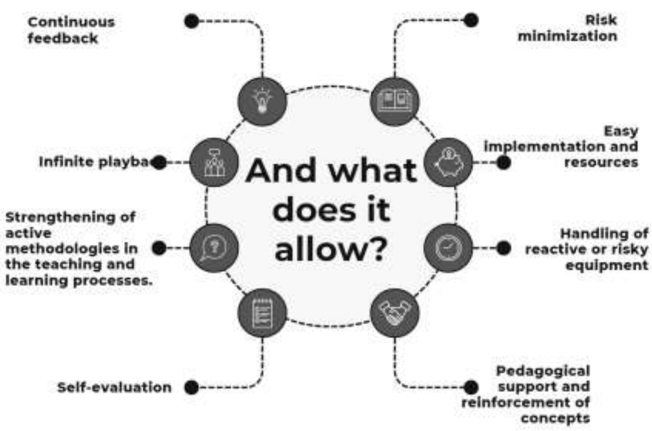
Adapted from [33]

Importance of virtual environments in teaching–learning processes

Virtual labs are programs that simulate a real environment and illustrate scientific phenomena. Virtual experiments have become experimental alternatives due to difficulties in accessing physical labs and provide an experience similar to that of a physical lab; in other words, virtual labs are not only limited to simulation but also provide real evidence (Orsega, Leonard, Ruggiero, Amato, & O´Hara, 2023), (Luque, Acosta, & Araujo, 2006), (Pascuas R, Bocanegra G., Ortiz L., & Pérez C, 2012), (Laboratorios virtuales y docencia de la automática en la formación Tecnológica base, 2015).

According to (Encalada & Pavón, 2016), (Martínez Vázquez & Hernández Pacheco, 2021), (Ayasrah, Alarabi, Mansouri, Fattah, & Al-Said, 2024), virtual environments in education foster students' interest in learning, enabling them to unfold efficiently with technological tools. Thus, experimental learning is strengthened, and several factors are manipulated to obtain variable results with multiple functions to assess different inputs, processes, and outputs. Fig. 2 illustrates the benefits of virtual labs:

FIGURE II. Benefits of Virtual Labs in Teaching–Learning Processes



Adapted from (Martínez Vázquez & Hernández Pacheco, 2021)

The authors of (Colado, 2019) identified two main trends in the use of technology for virtualization. One trend focused on the optimization of school infrastructure through virtual server technology, whereas the other focused on the creation and operation of virtual labs and educational environments. The authors highlighted access to academic infrastructure through the Internet, including labs, classrooms, tutorials, and administrative services.

Notably, virtual labs are a foundation that, supported by learning, close the existing gap in access, facilitate the provision of services, and improve students' academic performance (Zaldivar, 2019), (Combita, Parra, Torres, Pérez, & G Herrera, 2021), (Shen, Qi, Mei, & Sun, 2024). However, more complex processes are required to make theoretical classes virtual, and it becomes a challenge for teachers (Rosales & Pérez, 2023) as they must acquire digital competencies. These competencies have significant effects on results, experiences, learning quality, and education management, where intentionality plays a key role (Villarroel & Stuardo, 2022), (González & Lugo, 2020), (Factores determinantes en el uso del e-learning y la satisfacción docente, 2023).

Challenges Posed by Virtual Environments

Educational institutions face challenges in implementing strategies to reinforce learning processes (Tapia, Navarro, & De la Serna, 2017) while offering students not only quality education but also a sense of belonging (Vega, Sánchez, Rosano, & Amador, 2021). Both teachers and students have experienced critical

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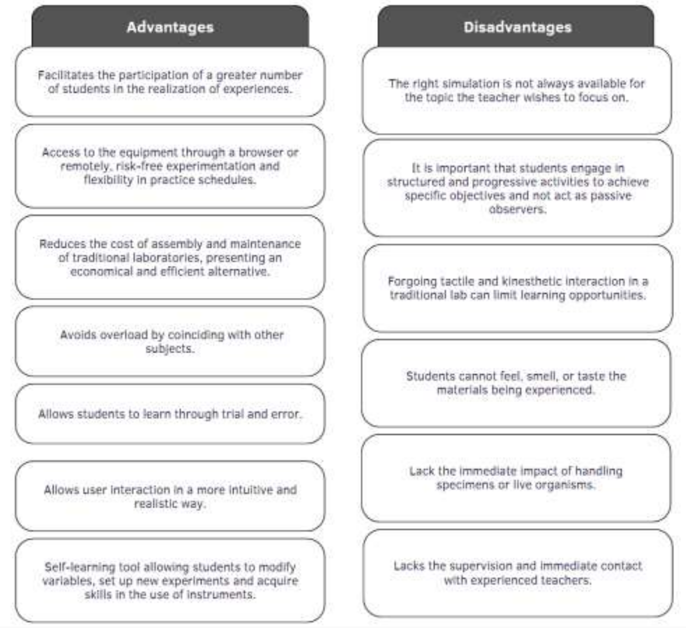
changes in how classes are conducted. Technology has played an active role and has overcome the limitations present in physical institutions, such as time and space (Huerta & Samaniego, 2023), (Ordoñez, 2021).

According to (Iriarte-Solis, 2010), despite the advantages of virtual labs, their limitations must also be considered, including the teacher's crucial role in supporting teaching processes. The use of new technologies, such as artificial intelligence, has been demonstrated as a strategy to mitigate these limitations. Fig. 3 presents the advantages and limitations of virtual labs:

FIGURE III. Advantages and Limitations of Virtual Labs



Adapted from (Iriarte-Solis, 2010)

Artificial intelligence is considered a powerful technology as it provides tools that can improve teaching practices. The use of different realities enables immersiveness in education through the creation of learning environments that result in practical and interactive experiences for students (Cárdenas Benavides, Carvajal Chavez, Tomalá de la Cruz, & Tovar Arcos, 2024). Virtual reality combines real environments with immersion in a digital environment, expanding how the senses capture reality and simultaneously combine them. Thus, teachers and students can interact through technological environments, thereby effectively acquiring knowledge and contents (Córcoles Ch., Tirado O.s, González C., & Cózar G., 2023), (Hernández, Bottner, Cataldo, & Zaragoza, 2021). Moreover, the Internet of Things (IoT) has acquired great importance as a teaching platform in various areas, including sciences and engineering, as it enables students to work and study remotely (Pereira, Patino, & Lata, 2022).

Construction of Virtual Labs

Virtual labs are an effective means to develop skills. They improve the immersive experience for students through the design of environments and interphases that are closer to reality, which requires analysis and expert consultation regarding how to create and implement them (Alvarez & Cabrera, 2020).

To build a virtual lab, (Guzmán, López B., & Torres, 2014) applied a systemic method proposed in (Castellanos & Martínez, 2010), in which each process is interconnected. The process begins with the design stage, in which the lab strategy is established and the requirements are gathered. Second, in the implementation stage, the virtual lab is programmed in a specific language based on the design and applied later. Finally, in the maintenance stage, modifications are made to the software after delivery to rectify any

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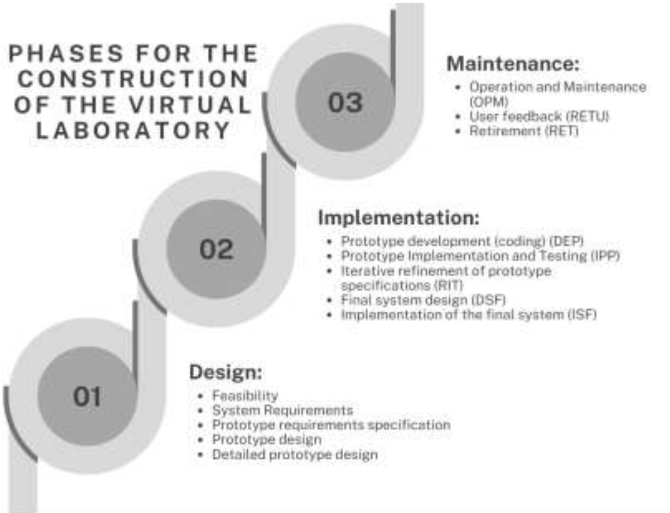
defects, improve performance, or adapt to changes in the environment. Fig. 4 depicts the three phases of constructing a virtual lab.

FIGURE IV. Construction Phases of a Virtual Lab



Adapted from (Guzmán, López B., & Torres, 2014), (Castellanos & Martínez, 2010)

According to (Riaño & Palomino, 2015), the selection of virtual labs is a complex decision, and adaptation and assessment are essential tasks. Thus, in (Riaño & Palomino, 2015), a hierarchical-analytical method was specified to reduce the gap between subjectivity and objectivity. The following aspects are the most important to consider: functionality, reliability, usability, efficiency, maintenance, and portability, in addition to technical, psycho-pedagogical, communication, and administrative aspects (Marqués, 2004), (Mendoza, M., & Grimán, 2005), (Jadhav, 2009), (Verma, 2008).

Discussion

The literature presents a positive perception regarding the potential of virtual labs. They enable teaching–learning processes to be optimized, the difficulties in accessing physical labs to be balanced, and knowledge to be acquired through enriching experiences.

The purpose of virtual labs is to enable accessibility with no restrictions. Investment by educational institutions is required to implement and maintain them, and their development should not be restricted to recreation but should also encompass the achievement of learning objectives.

Another aspect to consider is the lack of Internet access at some institutions, which creates difficulty in connecting to these platforms (Espinoza Castro, Apolo Buenaño, Sánchez Barrera, & Bravo Guzhñay, 2024). Nevertheless, virtual labs continue to be appropriate resources for overcoming the limitations of physical spaces.

Furthermore, technology has emerged as a positive solution to overcome the difficulties presented in labs, enabling students to conduct various practices according to class topics. Technology supports teaching–learning processes, individual work, and team work among students.

However, teachers must still provide pedagogical support. This is because digital resources—despite their great potential—would lack value without learning objectives, guidance from teachers, and any context for their development in a real environment. Similarly, experimental activities guide the acquisition of learning through practice, where not only are repetition and memorization applied but also meaningful learning, thus removing the barriers to knowledge acquisition (Carvajal, 2024).

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Nevertheless, the digital gap remains, posing a limitation to how virtual labs can overcome barriers in education. Educational policies that focus on fair access to information to improve teaching quality in all educational institutions are required.

Conclusion

Based on the literature that this study reviewed, it concluded that virtual labs are created to strengthen learning. They can be employed for any knowledge area and enable students to inquire and learn in a controlled, risk-free environment.

In their pursuit of strengthening teaching–learning strategies, educational institutions must implement technologies that foster progress in different research areas—both in physical and digital environments. Notably, however, the teacher is the main agent who must foster the use of ICT and adapt to the new demands and challenges.

Consequently, promoting environments that foster inquiry, cognitive stimulation, thirst for knowledge, and research becomes necessary, as does assessing the extent to which these tools must be adjusted to meet teachers and students' needs. Thus, environments can be established in which knowledge is acquired not only through theory.

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