International Journal of Education and Practice
2026 Vol. 14, No. 3, pp. 183-200
ISSN(e): 2310-3868
ISSN(p): 2311-6897
DOI: 10.18488/61.v14i3.5044

Intelligent virtual laboratories in higher education: Benefits and perspectives from an integrative review

Christian Lezama Cuellar[1+]
Lita Roman Bustinza[2]
Carmen Elvira Zavalaga Bustos[3]
Ysis Katherine Montoya Vereu[4]

[1]*Universidad Cesar Vallejo, Francisco Pizarro 391, Ayacucho, Peru.*
[1]*Email: chrilezamac@ucvvirtual.edu.pe*
[2]*Jose Faustino Sanchez Carrion University, Av. Mercedes Indacochea No. 609 – Huacho, Peru.*
[2]*Email: lroman@unjfsc.edu.pe*
[3]*Hermilio Valdizan National University of Huanuco, Av. Universitaria No. 601–607, Huanuco, Peru.*
[3]*Email: czavalaga@unheval.edu.pe*
[4]*Peruvian Technological University, Km 424 Panamericana Norte - Calle 56 S/N. Chimbote, Peru.*
[4]*Email: ymontoyav27@gmail.com*


(+ Corresponding author)

Article History
Received: 5 September 2025
Revised: 6 March 2026
Accepted: 12 June 2026
Published: 16 July 2026

Keywords
Artificial intelligence
Digital competencies
Higher education
Intelligent virtual laboratories
Inter-institutional collaboration.

ABSTRACT

Intelligent virtual laboratories (IVLs) are transforming higher education by integrating digital simulations, artificial intelligence, and accessibility, thereby enhancing access, autonomy, and the development of transferable skills. Additionally, these environments provide immersive and safe experiences that foster active learning and experimentation without incurring physical or financial risks. However, they face technological, pedagogical, instructional, and institutional challenges, as well as resistance and technological gaps. It is also essential to consider teacher training and technological infrastructure as key elements for the effective implementation of this initiative. This study aims to analyze the advantages and prospects of IVLs in universities, considering their pedagogical and strategic impact. A mixed-methods approach was employed, combining bibliometric analysis (utilizing Scopus, Python, and VOSviewer) with a systematic review (conducted using PRISMA). Recent and relevant studies on intelligent virtual laboratories in higher education were selected for review. Qualitative analysis was performed using ATLAS.ti, allowing for an in-depth and contextualized interpretation. Results show sustained growth in IVL-related publications since 2000, primarily in engineering, with a concentration in a few journals, and strong leadership from the Global North. After screening 2,187 records, 34 key articles were analyzed, highlighting the complex challenges IVLs face. Additionally, inter-institutional collaboration and formal certification emerge as crucial for consolidation and quality improvement. Finally, it is concluded that the future of innovative virtual laboratories will depend on global cooperation, educational innovation, and digital equity. In conclusion, IVLs are transforming higher education by expanding access and digital competencies, but require adequate institutional conditions and collaboration to overcome global gaps.

Contribution/Originality: This study contributes to the existing literature by integrating bibliometric analysis with an AI-supported systematic review. It is one of the few studies investigating global production gaps and institutional barriers, documenting how innovative laboratories transform higher education through digital equity and inter-institutional collaboration.

1. INTRODUCTION

The incorporation of emerging technologies in university education has profoundly altered traditional methods of teaching, learning, and research (Sembey, Hoda, & Grundy, 2024). In this context, where technological innovation intersects with the demands of academic development, intelligent virtual laboratories appear as instruments of notable transformation (Zhang et al., 2024). Rather than simply replicating processes, these platforms establish digital environments that enable experimentation and conceptual verification. They replicate laboratory conditions through controlled digital simulations, allowing practical work to be carried out in the absence of physical infrastructure. Thus, they create possibilities for interaction, customization, and access, shaping an educational model that redefines the boundaries between empirical experience and theoretical knowledge.

Beyond a simple technical improvement, this phenomenon implies a substantial pedagogical transformation. Because they incorporate artificial intelligence, laboratories not only process data in real-time but also adjust their functions to accommodate the learning styles of each student (Ezzaim, Dahbi, Aqqal, & Haidine, 2025; Lin, Wang, & Lan, 2022). Thus, they can provide specific feedback, facilitate the development of complex competencies, and, at the same time, ensure academic continuity in emergencies. This was the case during the COVID-19 pandemic, when these platforms enabled the continuation of formative practices without interruption (Bond, Bedenlier, Marín, & Händel, 2021). Additionally, their implementation reduces dependence on physical laboratories and significantly lowers the costs associated with infrastructure (Alkhatib, Qu, Cai, Unglaub, & Ritter, 2023).

However, its expansion has not been uniform. In specific institutional contexts, the adoption of these environments has encountered various forms of resistance. Among the primary barriers are limited teacher training in digital technologies, skepticism about virtuality as an effective medium for practical learning, and a lack of sustained technological investment (Shurygin, Ryskaliyeva, Dolzhich, Dmitrichenkova, & Ilyin, 2022). These difficulties raise legitimate doubts about its pedagogical effectiveness, the degree of its implementation, and its value compared with other educational methodologies.

For this reason, it is essential to conduct a study that is not limited to describing the technical characteristics of these tools. On the contrary, it is necessary to analyze their educational implications from a strategic perspective that considers both their benefits and the institutional conditions that favor or restrict their development. Understanding these factors will enable the development of a more comprehensive and practical understanding of their true potential.

In this framework, the present research assumes a dual responsibility: on the one hand, to clarify the fundamental concepts surrounding intelligent virtual laboratories; on the other, to provide systematic evidence to support informed decisions at the university level. This task becomes especially urgent when considering that many decisions about their adoption are still made based on perceptions, intuitions, or trends, without resorting to a rigorous analysis of existing knowledge.

In addition, this study has tangible social value, as it contributes to democratizing access to knowledge, strengthening institutional capacities, and enhancing the quality of education, particularly in contexts where resources are scarce. In this sense, addressing the subject not only responds to an academic concern but also to an ethical and political commitment to equitable access to quality higher education. From this perspective, the central question that guides the present study arises: What are the benefits, challenges, and prospects for implementing innovative virtual laboratories in university education?

1.1. General Objective

To analyze the benefits and perspectives of intelligent virtual laboratories in universities.

1.2. Specific Objectives

a) To identify the main research trends, the most influential authors, and the scientific journals with the highest impact that address the study of intelligent virtual laboratories in the university context.

b) To synthesize theoretical and empirical findings on the advantages, challenges, and projections of these tools in higher education and establish conceptual links that articulate their implications with institutional and academic transformations.

2. REVIEW OF LITERATURE

The literature on intelligent virtual laboratories in higher education has become increasingly relevant over the last decade, paralleling developments in artificial intelligence and immersive learning technologies. Several studies agree that these environments represent a convergence between the virtualization of scientific knowledge and the automation of pedagogical processes, which reconfigures the relationship among students, teachers, and digital resources (Alsaleh, Tepljakov, Köse, Belikov, & Petlenkov, 2022; El Kharki, Berrada, & Burgos, 2021; Qawaqneh, Ahmad, & Alawamreh, 2023). Within this framework, academic research has shifted from experimental approaches focused on technical effectiveness to broader perspectives examining its epistemological, institutional, and educational impact (Canright & White Brahmia, 2024; Errabo, Paguio, & Enriquez, 2024; Reeves & Crippen, 2021).

Recent studies broaden the focus to include the institutional benefits and pedagogical implications of adopting innovative virtual laboratories. In this field, their contributions to the expansion of remote education, the optimization of university resources, and the diversification of experimental experiences, all without dependence on physical infrastructure, are analyzed (Alkhaldi, Pranata, & Athauda, 2016; Tauber, Levonis, & Schweiker, 2022; Zhang & Liu, 2024). Likewise, the challenges arising from their implementation are explored, among which the need for teacher training, curriculum adaptation, and technological sustainability stand out (Elmoazen, Saqr, Khalil, & Wasson, 2023). These issues demonstrate that the transformative potential of innovative labs extends beyond learning to impact academic organization and the redefinition of the teaching role in algorithm-mediated environments.

From a theoretical perspective, the literature converges on the idea that innovative virtual laboratories constitute a space for articulation between artificial intelligence, digital pedagogy, and knowledge management (Klami, Damoulas, Engkvist, Rinke, & Kaski, 2024; Williamson, 2020). Their development involves a shift from the traditional teaching model to interactive schemes that integrate learning analytics and cognitive simulation as mechanisms for feedback and evaluation. Thus, research suggests that these tools not only optimize experimental learning but also shape new forms of production and circulation of university knowledge (Singh, Mantri, Sharma, & Kaur, 2021; Wang, Li, Chen, & Wang, 2025).

Taken together, the theoretical and empirical findings identify an expanding field of study that combines technological innovation with critical reflection on higher education. The literature reveals a dual dynamic: on the one hand, the consolidation of evidence demonstrating the effectiveness of innovative virtual laboratories in scientific learning, and on the other, the emergence of approaches that examine their institutional, ethical, and epistemological implications. Consequently, the analysis of their benefits and prospects cannot be separated from the processes of transformation that contemporary universities are undergoing, where digitization and artificial intelligence are redefining the foundations of teaching, research, and academic management.

3. RESEARCH METHODOLOGY

This research adopts a mixed approach, integrating quantitative and qualitative techniques to provide a comprehensive analysis of innovative virtual laboratories in the university setting. This methodological choice responds to the need to combine the statistical rigor of bibliometric analysis with the interpretive depth of systematic review, as this combination enables a broader understanding of the phenomena being studied. Authors such as Marzi, Balzano, Caputo, and Pellegrini (2025) argue that combining both approaches is essential for addressing complex phenomena in the social and educational sciences, as it promotes complementarity between empirical evidence and theoretical interpretation.

In the quantitative phase, a bibliometric analysis was conducted using the Scopus database, recognized for its comprehensiveness and reliability in the international scientific arena (Baas, Schotten, Plume, Côté, & Karimi, 2020). A search equation was incorporated that integrated key terms, including virtual intelligent laboratories, innovative labs, virtual labs, and higher education, which were combined using Boolean operators Table 1.

Table 1. Search equation.

Search equation	Descriptors	Operators
TITLE-ABS-KEY (("virtual lab" OR "virtual laboratories" OR "virtual intelligent laboratory" OR "virtual intelligent laboratories" OR "smart lab" OR "smart labs" OR "intelligent laboratory" OR "intelligent laboratories" OR "remote laboratory" OR "remote laboratories" AND ("higher education" OR "university"))	Virtual labs, intelligent laboratories, innovative labs, remote laboratories, higher education, university	OR, AND

These searches enabled the identification of the main research trends, the most cited authors, the journals with the highest impact, and the countries with the highest scientific output on the subject. Bibliographic data processing was performed using Microsoft Excel for initial organization, Python for advanced data analysis, and VOSviewer for visualization of co-occurrence, co-authorship, and co-citation networks, in accordance with the methodological recommendations Van Eck and Waltman (2010).

Subsequently, in the qualitative phase, a systematic literature review was conducted following the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Previously defined inclusion and exclusion criteria were applied, considering the publication period, language, document type (peer-reviewed articles), and thematic relevance (Table 2). This process enabled the purification of the initial corpus and ensured the quality and relevance of the analyzed studies.

Table 2. Article selection criteria.

Category	Inclusion criteria	Exclusion criteria
Period of publication	Publications between 2019 and 2024	Publications before 2019
Language	Studies in English or Spanish	Studies in other languages that cannot be translated easily
Type of document	Peer-reviewed scientific articles	Theses, papers, books, chapters, technical reports, and non-peer-reviewed documents
Thematic relevance	Studies focused on virtual, innovative, or remote laboratories in higher education	Studies not directly related to the use of virtual laboratories in university contexts
Access to the document	Full text available	Abstract only or without full access to the content

As stipulated by the PRISMA protocol, in the first phase, 2187 records were identified as depicted Figure 1. After eliminating 356 duplicate records, 1831 articles remained for screening, during which titles and abstracts were reviewed. As a result, 1594 were discarded for not meeting the established thematic and methodological criteria.

In the eligibility stage, 237 full texts were evaluated, of which 203 were excluded for not meeting at least one of the inclusion criteria, such as timeliness, thematic relevance, or methodological quality. Finally, 34 articles were selected and included in the systematic literature review phase.

Once the documents had been selected, the latest version of ATLAS.TI software, with artificial intelligence coding support, was used to carry out the qualitative content analysis. This tool facilitated open, axial, and selective coding of the texts, allowing emerging categories, recurring patterns, and significant conceptual relationships to be identified. Thus, the triangulation of quantitative and qualitative findings allowed for the construction of a solid and contextualized interpretation of the phenomenon studied, as it established links between the results and strengthened the coherence of the analysis. In addition, Copilot was used as a proofreading and style assistant to ensure consistency, clarity, and accuracy in the writing of the results and discussions, without altering the integrity of the original content.

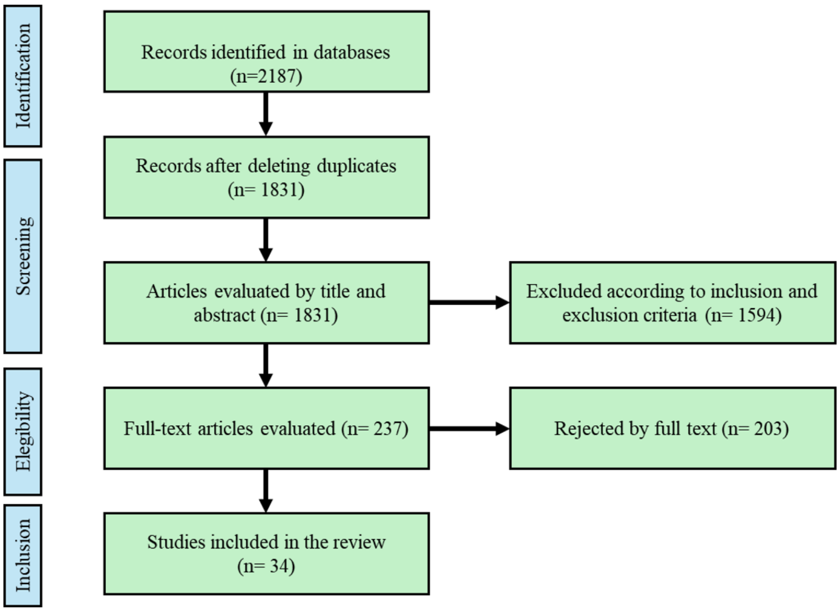

Figure 1. PRISMA flow.

4. FINDINGS

4.1. Bibliometric Analysis

The bibliometric analysis reveals a progressive evolution in the annual frequency of publications related to intelligent virtual laboratories from 1992 to 2025, as illustrated in Figure 2. During the 1990s, production was practically nil: between 1992 and 1999, there were between 0 and 7 publications per year, indicating an incipient and unconsolidated interest.

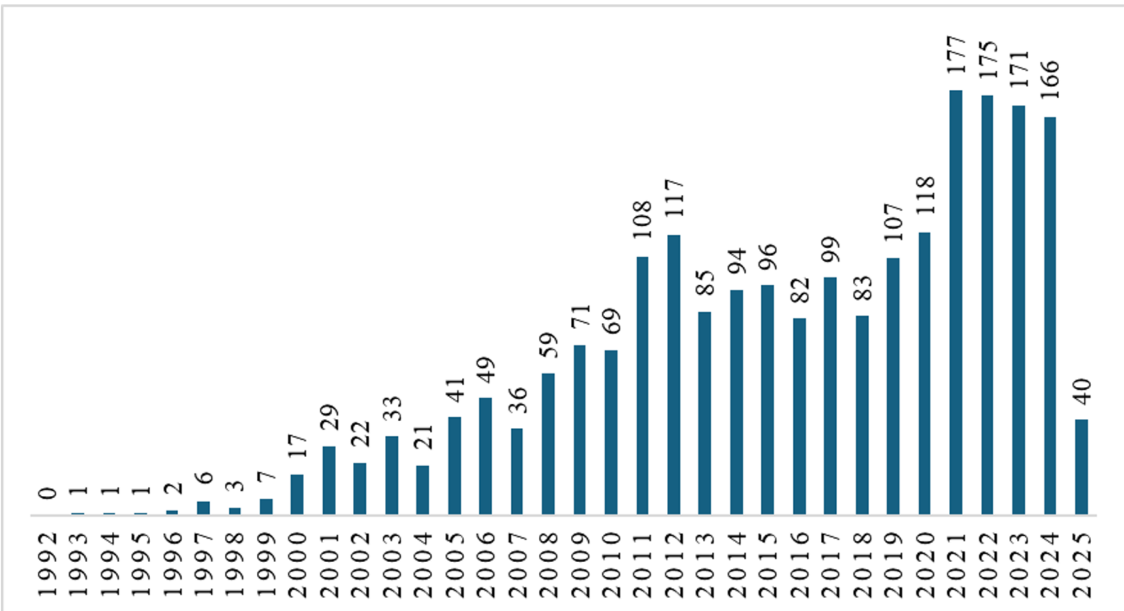

Figure 2. Annual frequency of publication.

From 2000 onwards, an important change can be observed. The frequency of publications increases gradually, reaching 17 records that year and 29 in 2001. In the period between 2002 and 2010, production grew steadily and reached a peak of 71 publications in 2009. In the following decade, academic interest consolidates. From 2011 to 2014, the frequency of publications exceeded 90 annual records, and in 2012, 117 publications were reached. In 2015, 96 publications were recorded, and the figure remained above 80 until 2019. The upward trend continues with greater intensity from 2020 onwards. That year, 118 publications were recorded, while in 2021, the historical maximum of 177 records was reached. The following years maintain high figures: 175 in 2022, 171 in 2023, and 166 in 2024.

In total, between 2015 and 2024, 1,274 publications have been recorded, representing 59.1% of the overall total of 2,156 studies identified in the entire period analyzed. This data evidences that most of the scientific production on intelligent virtual laboratories has been generated in the last ten years, confirming the increase in academic and technological interest in this line of research. Therefore, the field has gone from being an emerging proposal to becoming a central axis within innovations applied to education and digital experimentation.

However, scientific production on intelligent virtual laboratories is concentrated in a small group of journals and is not distributed homogeneously, as depicted in Figure 3. The ten journals with the highest frequency have 458 articles, representing 21.2% of the total 2,156 records.

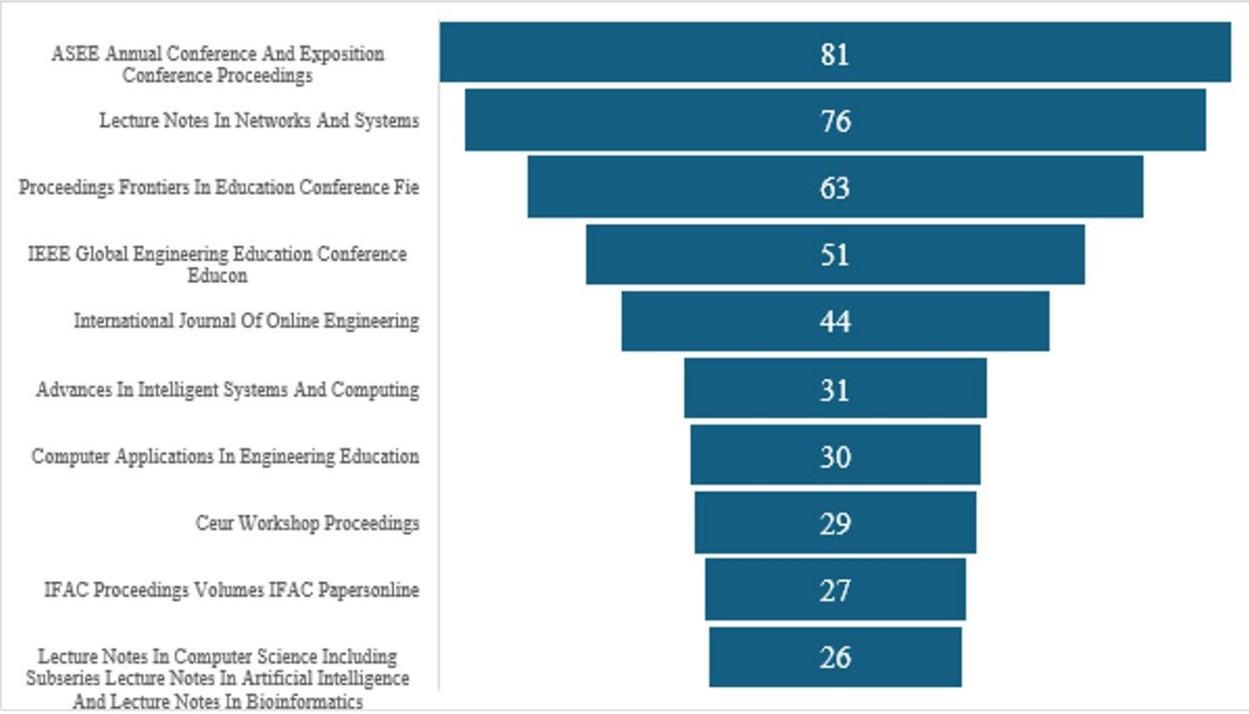

Figure 3. Frequency of publication by journal.

In first place is ASEE Annual Conference and Exposition Conference Proceedings, with 81 publications; it is followed by Lecture Notes in Networks and Systems, which has 76 articles. In third place is Proceedings Frontiers in Education Conference (FIE), with 63 indexed papers. These three sources account for more than 10% of the total production, demonstrating their relevance in the field.

Next comes the IEEE Global Engineering Education Conference (Educon), with 51 publications, while the International Journal of Online Engineering ranks fifth with 44 articles. Following that is Advances in Intelligent Systems and Computing, with 31 contributions, and then Computer Applications in Engineering Education, with 30. CEUR Workshop Proceedings has 29 articles, and IFAC Proceedings Volumes/IFAC PapersOnline has 27. The group is completed by Lecture Notes in Computer Science (LNCS), which includes 26 papers, among them contributions on artificial intelligence and bioinformatics applied to engineering education.

In contrast, the remaining 130+ journals account for 78.8% of the articles, indicating a wide dispersion in the publication of research on this topic. This distribution shows considerable fragmentation in the sources of publication, although it also reveals the cross-cutting interest that intelligent virtual laboratories generate. This diversity reflects the cross-cutting interest in intelligent virtual laboratories, as they involve disciplines such as engineering, technology education, applied informatics, and industrial automation. Although the output is spread across multiple approaches, the set of most-cited journals maintains a defined orientation towards engineering education and educational technologies, which confirms the technical and formative nature of this line of research.

On the other hand, universities with the greatest presence in academic production on innovative educational practices are concentrated in Europe and Latin America, as indicated in Figure 4. In this context, the institutions with the greatest participation are concentrated in these regions, where the National University of Distance Education leads the list with 78 publications, followed by the University of Deusto with 55 and the Monterrey Institute of Technology with 34.

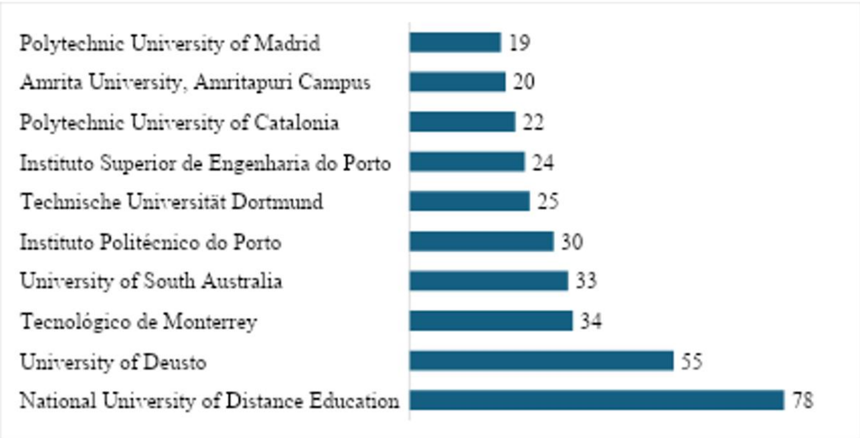

Figure 4. Affiliation impact.

This is followed by institutions such as the University of South Australia (33), the Instituto Politécnico do Porto (30), and the Technische Universität Dortmund (25), all with a strong focus on methodological innovation in the university environment. Also noteworthy is the presence of Spanish universities such as the Universitat Politècnica de Catalunya (22), the Universidad Politécnica de Madrid (19), the Universidad de Salamanca (13), and the Universidad de Alcalá (12). The Portuguese panorama is also significant, as the Instituto Superior de Engenharia do Porto (24) and the Universidade do Porto (16) were identified. Italian universities such as the Università degli Studi del Sannio (11) and the Università di Pisa (6) join this trend.

In Latin America, the Tecnológico de Monterrey (34) and the Universidad Nacional de Rosario (10) lead the group. Also present are the Universidad Nacional Abierta y a Distancia (6) and the Universidad de Buenos Aires (5). Universities such as the Massachusetts Institute of Technology (16), the University of Illinois Urbana-Champaign (9), and the Georgia Institute of Technology (6) have also conducted research in virtual laboratories.

However, regarding the geographical distribution of publications, a clear gap between the global north and south in academic production can be observed, as shown in Figure 5. The United States leads with 341 records, followed by Spain with 315, indicating the dominance of countries from the global north in the scientific arena. Germany (145), China (100), Australia (95), Italy (94), Portugal (83), and the Russian Federation (81) reinforce this dominance, while the United Kingdom (79) and India (77) complete the group of nations with the highest publication volume. Although India and China are in Asia, their influence is more due to their economic and technological capacity than their belonging to the global south in the strict sense.

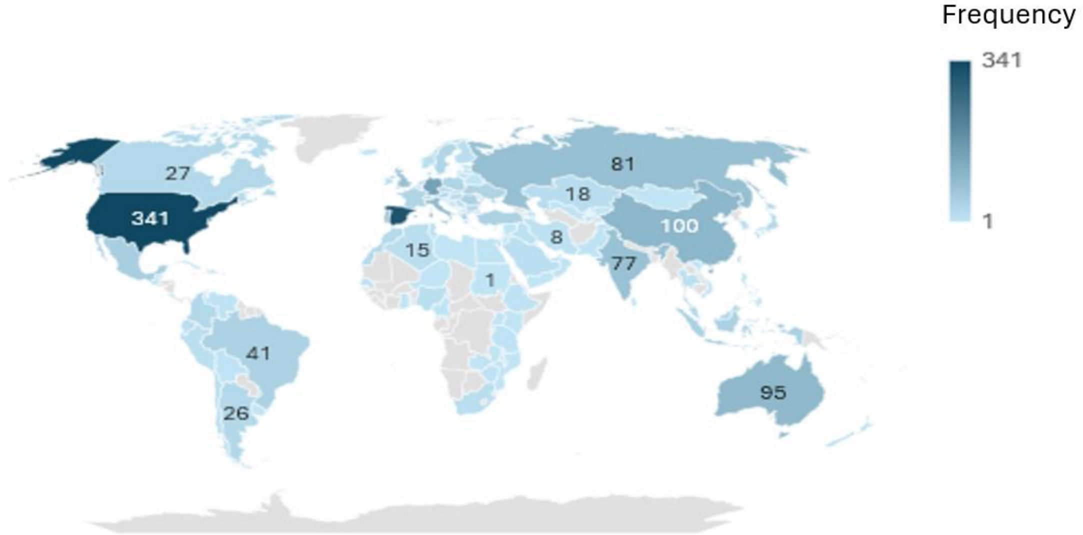

Figure 5. Countries with the highest publication impact.

The quantitative superiority of the global North is confirmed not only by the frequency of registrations but also by the density of Western European countries at the top of the ranking. France (36), Sweden (33), Austria (31), the Netherlands (23), Switzerland (24), Finland (14), Denmark (13), Norway (15), Ireland (10), and Belgium (11) form a compact block which, although not leading in absolute terms, maintains a constant and structured production. In turn, Canada (27) and Japan (25) reinforce this logic from their regions, and although their figures do not reach those of the United States, they confirm their integration into the central scientific system.

In contrast, the global south appears dispersed and with marginal participation. Latin America has few outstanding representatives: Mexico (46) leads the region, followed by Colombia (27), Argentina (26), Brazil (41), Chile (15), Peru (12), Cuba (7), Venezuela (4), Ecuador (14), and Uruguay (1). These data show that the region is not absent, but its participation is fragmented and depends on local dynamics that fail to sustain a robust presence. Despite their large populations and pressing social needs, these countries have not been able to build scientific systems that compete in volume with those of the North.

Similarly, African countries have an even more limited participation. South Africa, with 15 records, stands out as the main reference for the continent, followed by Algeria (15), Nigeria (12), Egypt (4), and Morocco (25), with several countries contributing only one or two, such as Ghana, Mozambique, Uganda, Tanzania, Zambia, and Rwanda. This scarce production is not due to a lack of intellectual capacity but results from structural conditions like limited public funding, dependence on international cooperation, and institutional precariousness.

In Asia, the panorama also reproduces inequalities. Although China and India occupy high positions, their rise responds more to state policies of investment in science than to a structural belonging to the South. On the other hand, countries such as Indonesia (43), Turkey (42), Iran (8), Iraq (8), Jordan (14), and the Philippines (6) maintain more modest figures and show a peripheral positioning. Additionally, the Gulf countries, such as Saudi Arabia (11), the United Arab Emirates (10), Qatar (8), and Kuwait (5), show controlled growth, sustained by economic resources rather than consolidated academic trajectories.

On the other hand, the analysis according to thematic areas shows an absolute dominance of engineering, which concentrates 1166 records and confirms its position as the structuring axis of academic production, as highlighted in Figure 6. This is followed by computer science, with 1079 publications, indicating that algorithmic logic and digital development are central to research priorities. The field of social sciences follows with 867 records, representing a relevant contrast with the technical block. Although it does not outnumber technological areas, its volume indicates a sustained concern for political, cultural, and urban phenomena.

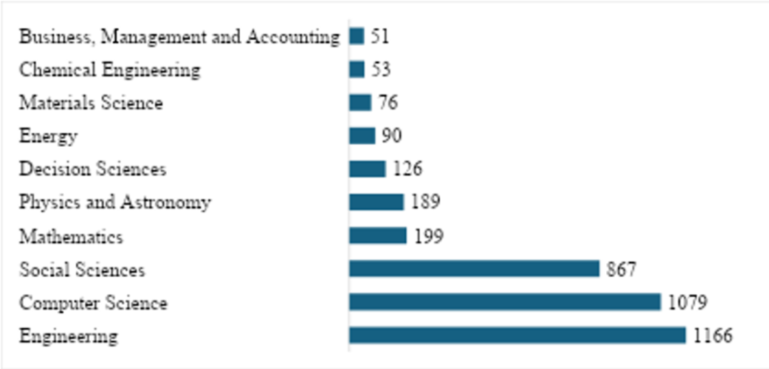

Figure 6. Area of greatest publication impact.

In the group of disciplines with an intermediate presence, mathematics (199) and physics and astronomy (189) stand out, offering abstract models, formal solutions, and predictive frameworks with high instrumental value. Added to this set are decision sciences, with 126 publications, which articulate instruments for the optimization and rational design of policies and processes; their contribution establishes a bridge between theoretical modeling and applied management. Further down the list are areas such as energy (90), materials science (76), chemical engineering (53), and management and accounting (51). Similarly, chemistry (49), medicine (42), and molecular biology (40) complete this block, in which knowledge is oriented towards technical interventions of structural impact.

The next levels are psychology (38), environmental science (37), agriculture and biology (21), health professions (20), and the arts and humanities (19). This set has a more contextual character, as it explores social, territorial, and symbolic processes whose resolution exceeds the limits of the laboratory or computational calculation; its function lies not in quantity but in the ability to reveal subjective, historical, and ecological dimensions that technical approaches usually omit.

Close to the margin are the planetary sciences (16), multidisciplinary research (11), and economics and finance (10), which do not disappear, but neither do they form gravitational cores within the system. These are joined by pharmacology (7), neuroscience (4), immunology (2), and dentistry (1), whose minimal presence suggests that specialized biomedical sciences do not constitute the focus of attention of the analyzed set.

On the other hand, the analysis presented in Figure 7 allows us to observe how the words most frequently used in the titles and abstracts of the papers examined are organized and intertwined. Far from a random distribution, the graph reveals a semantic architecture composed of clearly differentiated thematic nuclei, whose dimensions, positions, and connections reflect the dominant orientation of research in the area.

One of the most prominent blocks appears in green and is headed by terms such as remote laboratory, internet, and interface, which are not only repeated with greater frequency but also articulate a technological discourse centered on the virtualization of learning environments. Around these terms, other concepts such as practical work, microcontroller, and parameter emerge. In a different direction, the red cluster groups words such as COVID, motivation, impact, and test semester. This cluster refers directly to the pandemic context but also accounts for institutional and pedagogical responses to the crisis. It is not only a conjunctural reference but a field of analysis that examines the link between external conditions, methodological changes, and effects on the learning experience. The presence of terms such as student motivation and readiness reinforces this reading.

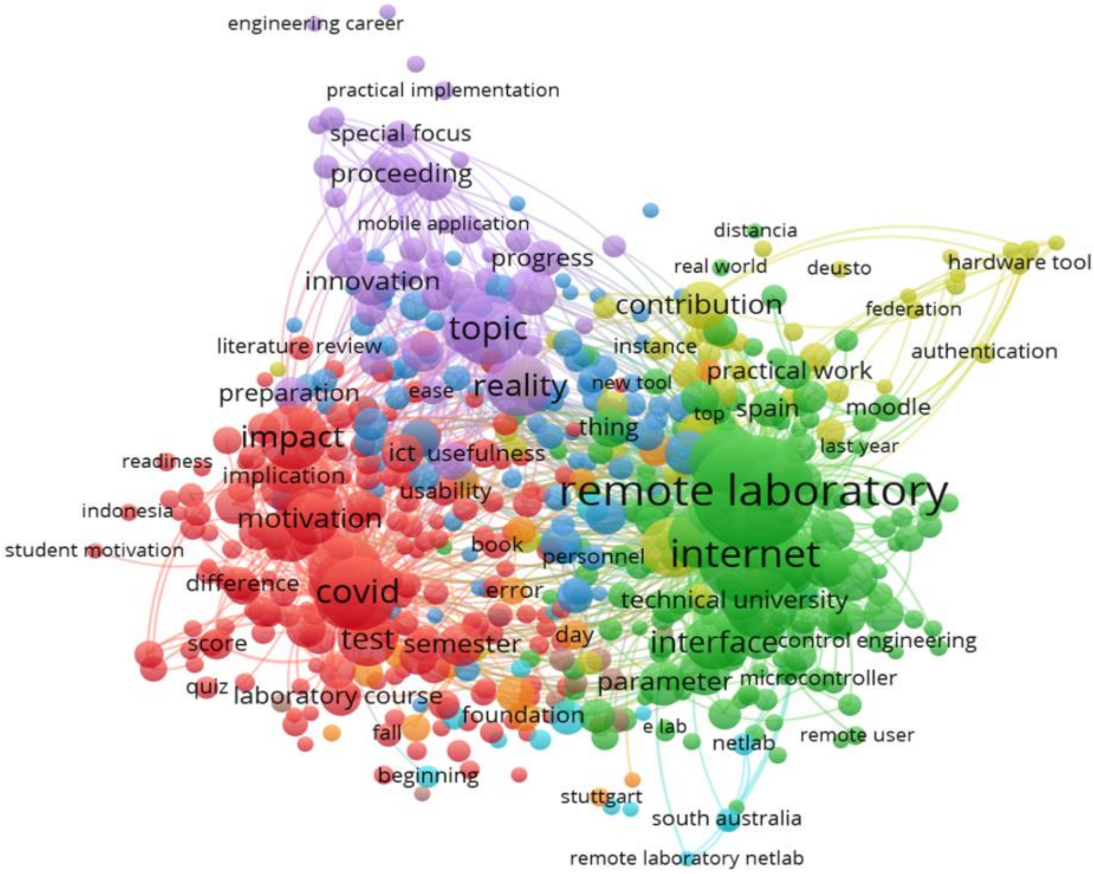

Figure 7. Analysis of most concurrent words in the abstract and title.

On the other hand, the purple sector of the graph is made up of expressions such as innovation, progress, special focus, and topic, which suggest a more abstract or conceptual orientation. This group seems to be nourished by papers that not only describe applied technologies but also reflect their implications in the medium and long term, while outlining possible future agendas.

Finally, at the ends of the graph, there are smaller groupings, such as the yellow one, where words such as Moodle, authentication, hardware tool, and federation stand out. Although these nodes have a lower frequency, their thematic concentration indicates the existence of specialized niches, often linked to specific institutional experiences or technical developments.

4.2. Systematic Literature Review

4.2.1. Challenges of Virtual Laboratories In Universities

One of the main challenges identified relates to the technological infrastructure of universities. Several studies (Hernández, Pérez, & López, 2020; Silva & Romero, 2022) argue that many institutions lack powerful servers, high-speed networks, or adequate devices to support the smooth operation of virtual laboratories, which causes frequent interruptions and affects the continuity of practical experiences. Likewise, it was identified that unequal access to technology by students generates a learning gap. While some access from personal devices with a stable connection, others depend on institutional equipment with restricted schedules, which limits their autonomy and reduces effective interaction time with the simulations.

In addition to technological problems, challenges related to the pedagogical design of virtual laboratories have arisen. Research such as that of González and Méndez (2021) and Flores, Ramírez, and Hernández (2023) agrees that many virtual environments replicate traditional models focused on the mechanical execution of procedures, without integrating active methodologies or encouraging critical reflection. In this sense, it was observed that the transition from the physical to the virtual laboratory does not always imply a didactic redesign, but a mere digitalization of practices. This situation generates learning experiences that are not very meaningful, reduces student interest, and affects the appropriation of experimental competencies, especially in areas such as chemistry, physics, and biology.

On the other hand, it was found that the faculty faces significant obstacles to incorporating virtual laboratories into their practices. Although most recognize their potential value, numerous studies pointed to the lack of specific training in the use of platforms, the limited availability of time to adapt content, and resistance to change as limiting factors. Authors such as Almqvist and Werner (2024) highlighted that, in contexts where a conservative institutional culture prevails, pedagogical innovation is perceived as a threat rather than an opportunity. Therefore, the effective implementation of virtual laboratories requires not only technological competencies but also adequate working conditions, academic incentives, and committed institutional leadership.

At the organizational level, limitations linked to institutional management and project sustainability were also identified. The review showed that many universities promote virtual laboratory initiatives through temporary funding or as a temporary response, without integrating them into their medium- or long-term strategic plans (El Kharki et al., 2021; Kolil & Achuthan, 2024; Marks & Thomas, 2022). This lack of structural vision prevents the consolidation of permanent technical teams, the continuous updating of platforms, and the maintenance of digital resources. Additionally, little articulation was detected between academic, technical, and administrative areas, which slows decision-making, hinders system interoperability, and fragments innovation processes (Kenny & Fluck, 2022; Khahro, Shaikh, Zainun, Sultan, & Khahro, 2023).

Taken together, the challenges described above make it evident that the implementation of virtual laboratories cannot be approached exclusively from a technological perspective. The findings of the systematic review show that a comprehensive vision is required, in which pedagogical decisions, institutional policies, and teacher training strategies converge. It is also essential to establish continuous evaluation mechanisms to monitor the quality of virtual experiences, collect student feedback, and adjust digital environments according to real learning needs.

It is important to note that, although virtual laboratories are a promising alternative to expanding access to practical experiences, their effectiveness depends on multiple interrelated factors. Therefore, overcoming the challenges identified requires not only investment in technology but also a profound transformation in academic cultures, teaching models, and the way universities conceive experiential education in digital environments. In sum, the systematic review reveals that the success of virtual laboratories will depend on the ability of institutions to integrate innovation with equity, sustainability, and pedagogical relevance.

4.2.2. Benefits and Projections of Virtual Laboratories in the University Context

Among the most outstanding benefits, the broadening of access to practical experiences was identified as one of the most significant contributions. Unlike traditional laboratories, virtual environments allow students to interact with simulations from any location and at flexible times, which reduces the spatial and temporal barriers that often limit student participation in experimental activities (Hu-Au & Okita, 2021). Research such as Miller, Marks, and Thompson (2025) and Kapilan, Vidhya, and Gao (2021) demonstrated that this flexibility fosters student autonomy, strengthens time management, and allows for the repetition of procedures as many times as necessary. Furthermore, it establishes a direct relationship between constant practice and a deep understanding of phenomena, generating purposeful learning.

Another widely documented benefit was the optimization of institutional resources. Several authors have argued that the implementation of virtual laboratories streamlines the use of physical supplies, reduces costs associated with equipment maintenance, and decreases risks from handling hazardous substances (Alsaleh et al., 2022; Klami et al., 2024; Ni, Li, Xu, Yu, & Wang, 2022). Consequently, this environment is an effective alternative for academic programs requiring constant practice, even with limited infrastructure. Authors such as Li and Liang (2024) and Poo, Lau, and Chen (2023) emphasized that, in budget-restricted contexts, virtual laboratories enable maintaining training quality without compromising security or pedagogical standards.

Likewise, the literature analyzed showed that virtual laboratories favor the development of digital competencies and transversal skills (Hsu, Bowden, & Acosta, 2025; Machwate, Bendaoud, Henze, Berrada, & Burgos, 2021; Wu, Manabe, Marek, & Shu, 2023). Through these platforms, students apply technical knowledge, strengthen observation skills, and combine logical reasoning with problem-solving in technological environments. Additionally, several studies highlight that simulation tools allow the integration of different knowledge areas and exploration of variables impossible to manipulate in real conditions, broadening educational scope and consolidating a more articulated university education in its theoretical and practical dimensions.

Regarding projections, most of the reviewed studies conclude that virtual laboratories will not displace physical spaces entirely, yet they will establish themselves as a stable and enduring element within hybrid teaching frameworks. This complementarity will make it possible to design more dynamic teaching sequences, combine the best of both environments, and respond with greater agility to emergencies, as occurred during the COVID-19 pandemic. In turn, prospective studies (Nakata, Sato, Tanaka, & Yamamoto, 2024; Ruiz & Caballero, 2023) suggest that in the coming years, the use of emerging technologies such as augmented reality, artificial intelligence, and gamification will increase to strengthen interactivity and personalization of practices.

In addition, sustained growth is projected in inter-university collaboration for the design of shared virtual laboratories. Moreover, the analysis revealed an expansion of cooperative frameworks among institutions, and such coordination enables the joint creation of digital infrastructures that multiply access to experimental simulations while optimizing available resources. The review showed successful experiences in which different institutions co-developed platforms that allow access to a wide range of simulations, which optimizes the use of resources and fosters regional academic cooperation (Qiao, Xu, Li, & Ouyang, 2021; Yuan & Wu, 2020). Consequently, these projects establish a foundation for academic interdependence and reinforce the collective capacity to respond to technological challenges. This type of initiative represents a strategic opportunity for universities with lower levels of investment, as it allows them to access state-of-the-art technologies without incurring high in-house development costs. Thus, collaboration functions as a mechanism of equity and innovation across diverse institutional contexts.

Finally, an emerging trend was identified toward the certification of experiential competencies acquired in virtual environments, which would make it possible to formalize the learning obtained and guarantee its recognition in work environments (Harris, Bird, Smart, Wilson, & Vine, 2020; Jallad & Işık, 2025). In addition, the consolidation of such certification systems presupposes negotiation between academic authorities and regulatory entities, and this interaction defines new parameters for educational validity. This progress will require the creation of common quality standards, the validation of simulations as reliable pedagogical tools, and the articulation with accrediting bodies. As a result, the institutional framework will expand toward a model where practical digital experience becomes a verifiable indicator of professional competence. Although this process is still in a preliminary phase, its realization will strengthen the link between universities and the professional market and will contribute to a more relevant education adapted to the demands of the 21st century. Therefore, the evolution of these mechanisms anticipates a redefinition of academic certification and its correspondence with productive sectors.

Thus, the benefits of virtual laboratories in the university context are not limited to technical or logistical aspects but include pedagogical, economic, institutional, and prospective dimensions. In this sense, their influence extends across the architecture of higher education and introduces a logic of systemic transformation sustained by innovation and cooperation. Their future development will depend on the capacity of universities to innovate in their didactic strategies, build collaborative alliances, and take on the challenge of training professionals capable of developing in complex, flexible, and digitalized environments. Only through such integrative capacity will virtual laboratories evolve from auxiliary instruments into essential vectors of academic modernization. The systematic review allows us to affirm that virtual laboratories represent not only a support tool but also a key element in the structural transformation of contemporary higher education. Hence, they emerge as catalysts of institutional change and as central components in the configuration of a new academic paradigm.

5. DISCUSSION

The mixed methodological approach used in this study made it possible to achieve a comprehensive understanding of intelligent virtual laboratories (IVLs) in higher education, as it combined the quantitative precision of bibliometric analysis with the interpretative depth of the systematic review. This methodological articulation allowed not only the recognition of structured scientific tendencies but also the exposition of the practical circumstances that determine their presence within academic contexts, since it integrated analytical rigor with reflective examination. This strategy, endorsed by Marzi et al. (2025), facilitated the identification of consolidated scientific patterns and, at the same time, provided a critical look at the actual conditions of implementation in university settings.

First, the bibliometric analysis showed sustained growth in scientific production on IVL, especially from 2015 onward. This evolution revealed the consolidation of research trajectories and the progressive structuring of thematic cores within the field, reflecting a cumulative dynamic linking institutional initiatives with technological expansion. Moreover, the temporal convergence between this increase and digital transformation processes in education exposed the interdependence between innovation policies and the preservation of academic activity under exceptional circumstances. This trend coincided with the advancement of educational digitization and the need to maintain academic continuity during the COVID-19 pandemic, as pointed out by Bond et al. (2021). On the other hand, Zhang et al. (2024) and Sembey et al. (2024) also highlighted that this increase not only reflects greater academic interest but also confirms the consolidation of IVLs as strategic axes within contemporary educational innovations.

However, the data also showed a thematic and geographic concentration. On the one hand, most publications were in areas such as engineering and computer science, which reaffirms the technical nature of the field. On the other hand, the countries of the global north dominated academic production, while the nations of the global south participated in a fragmented and limited way. This inequality was noted by authors such as Almqvist and Werner (2024), who linked the lag of certain regions to structural factors such as lack of funding, institutional precariousness, and poor articulation between educational policies and scientific agendas.

Secondly, the systematic review made it possible to understand that the development of IVL is not without its challenges. Many universities face technological barriers, such as the lack of powerful servers or stable networks, which compromise the continuous operation of these platforms, as pointed out by Hernández et al. (2020) and Silva and Romero (2022). In addition, problems related to pedagogical design were identified, as many laboratories replicate traditional models without introducing substantive didactic innovations. González and Méndez (2021) and Flores et al. (2023) agreed that these limitations reduce the formative impact of virtual environments and decrease student interest.

However, faculty face institutional obstacles. Although many teachers value the educational potential of IVLs, they also express difficulties in adapting their content, accessing specialized training, or having the necessary time to redesign their strategies. Almqvist and Werner (2024) warned that these difficulties are exacerbated in contexts where conservative institutional cultures prevail, as pedagogical innovation is often perceived as a threat rather than an opportunity. Therefore, universities need to generate adequate working conditions, academic incentives, and leadership committed to educational transformation.

In contrast to these limitations, the review documents multiple relevant benefits. IVLs expand access to hands-on experiences, allow students to work flexible schedules, and reduce physical barriers to experiential learning. Kapilan et al. (2021) and Hu-Au and Okita (2021) highlighted that these conditions strengthen student autonomy and enhance understanding of complex phenomena.

In addition, virtual platforms optimize resource utilization, reduce costs, and minimize risks, as demonstrated by the studies of Alsaleh et al. (2022) and Ni et al. (2022). These benefits translate into sustainable solutions, especially for programs that require intensive practice but lack sufficient physical infrastructure.

Also, IVLs foster the development of cross-cutting skills. Hsu et al. (2025) and Wu et al. (2023) demonstrated that students using these platforms strengthen their logical thinking, improve their problem-solving skills, and develop digital competencies useful for their professional performance. Therefore, IVLs are not only a technological resource but also a pedagogical tool that fosters a more comprehensive and contextualized education.

Regarding projections, the studies reviewed agreed that IVLs will not completely replace physical laboratories, although they will be definitively integrated into hybrid teaching models. However, the authors agreed that this integration will consolidate a functional balance between both spaces and transform academic methodologies. Ruiz and Caballero (2023) and Nakata et al. (2024) pointed out that this complementarity will allow combining the best of both environments, adapting to emergencies, and designing more dynamic learning experiences. They also highlighted that the integration of physical and virtual environments will promote educational continuity and reconfiguration of the training process. Additionally, an expansion of the use of technologies such as artificial intelligence, augmented reality, and gamification is foreseen, which will facilitate the personalization of practices and raise the quality of feedback (Ezzaim et al., 2025; Lin et al., 2022). Likewise, a sustained increase in the implementation of technological resources is expected, which will optimize didactic interaction and improve evaluation mechanisms.

On the other hand, interinstitutional collaboration is emerging as a key strategy to overcome access and funding constraints. Similarly, cooperation between institutions is emerging as a structural instrument to expand educational coverage and rationalize available resources. Qiao et al. (2021) and Yuan and Wu (2020) documented successful experiences of shared development of platforms, which allowed expanding the supply of simulations and fostering regional academic networks. Consequently, the joint creation of digital infrastructures strengthened academic ties and fostered the equitable distribution of knowledge. This modality represents an opportunity for universities that do not have a large budget but aspire to offer quality training with cutting-edge technology. Therefore, this alternative redefines the possibilities for institutional innovation and expands the educational scope in contexts of economic constraint.

Finally, there was an emerging trend toward formal certification of competencies acquired in virtual environments. Additionally, a trend was identified toward institutionalizing the recognition of skills developed in digital spaces. Harris et al. (2020) and Jallad and Işık (2025) pointed out that this validation will enable recognition of learning in work contexts and strengthen the link between universities and the professional market. In this sense, formal accreditation will consolidate the correspondence between academic training and job performance and redefine educational legitimacy parameters. To achieve this, it will be necessary to establish quality standards, reliable evaluation mechanisms, and agreements with accrediting bodies. Therefore, constructing regulatory frameworks, adopting verifiable evaluation systems, and coordinating with certifying bodies.

6. CONCLUSIONS

Intelligent virtual laboratories (IVL) have established themselves as key tools in the transformation of higher education, since they allow broadening access to practical experiences, optimizing institutional resources, and fostering the development of digital competencies. Far from being a simple technological resource, IVLs are configured as pedagogical spaces that can contribute to a more autonomous, flexible, and relevant training for the challenges of the 21st century.

However, their effective implementation does not depend exclusively on technical progress but on institutional, political, and formative conditions that allow integrating these tools into educational processes strategically. The findings of this study show that significant gaps persist in the adoption of IVL, particularly in regions of the global south, where scientific production is still limited and structural conditions hinder the consolidation of these initiatives.

The strong concentration of research in countries of the global North highlights an asymmetry in the generation and circulation of knowledge. This situation not only limits the visibility of local experiences but also reduces the possibility of building contextualized pedagogical models that respond to the needs and realities of the most vulnerable educational systems. Therefore, it is urgent to promote lines of research that prioritize regional diversity, promote inter-institutional collaboration, and strengthen the scientific capacities of the global South.

Based on these findings, there are multiple opportunities for future research. It is necessary to explore in greater depth how IVL can be adapted to contexts with technological restrictions, what pedagogical strategies enhance their effectiveness, and how they can contribute to closing the gaps in access to practical education in historically excluded populations. Likewise, it is recommended to investigate the validation of competencies acquired in virtual environments and the construction of quality standards that guarantee their recognition in professional environments.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Alkhaldi, T., Pranata, I., & Athauda, R. I. (2016). A review of contemporary virtual and remote laboratory implementations: Observations and findings. *Journal of Computers in Education*, *3*(3), 329-351. https://doi.org/10.1007/s40692-016-0068-z

Alkhatib, M., Qu, Y., Cai, R., Unglaub, R. A. G., & Ritter, R. (2023). Real time virtual laboratory solution prototype and evaluation for online engineering degree programs. *IEEE Access*, *11*, 130508-130516. https://doi.org/10.1109/ACCESS.2023.3334262

Almqvist, C. F., & Werner, A. (2024). Maintaining and challenging conservative teaching and learning culture in conservatories: The need for holistic pedagogy in educational fields of tension. *Research Studies in Music Education*, *46*(2), 257-270. https://doi.org/10.1177/1321103X231187766

Alsaleh, S., Tepljakov, A., Köse, A., Belikov, J., & Petlenkov, E. (2022). ReImagine Lab: Bridging the gap between hands-on, virtual and remote control engineering laboratories using digital twins and extended reality. *IEEE Access*, *10*, 89924-89943. https://doi.org/10.1109/ACCESS.2022.3199371

Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quantitative Science Studies*, *1*(1), 377-386. https://doi.org/10.1162/qss_a_00019

Bond, M., Bedenlier, S., Marín, V. I., & Händel, M. (2021). Emergency remote teaching in higher education: Mapping the first global online semester. *International Journal of Educational Technology in Higher Education*, *18*(1), 50. https://doi.org/10.1186/s41239-021-00282-x

Canright, J. P., & White Brahmia, S. (2024). Modeling novel physics in virtual reality labs: An affective analysis of student learning. *Physical Review Physics Education Research*, *20*(1), 010146. https://doi.org/10.1103/PhysRevPhysEducRes.20.010146

El Kharki, K., Berrada, K., & Burgos, D. (2021). Design and implementation of a virtual laboratory for physics subjects in Moroccan universities. *Sustainability*, *13*(7), 3711. https://doi.org/10.3390/su13073711

Elmoazen, R., Saqr, M., Khalil, M., & Wasson, B. (2023). Learning analytics in virtual laboratories: A systematic literature review of empirical research. *Smart Learning Environments*, *10*(1), 23. https://doi.org/10.1186/s40561-023-00244-y

Errabo, D. D., Paguio, A. J., & Enriquez, P. A. (2024). Epistemic fluency in virtual laboratories as flipped classroom's innovative learning delivery. *Journal of Research in Innovative Teaching & Learning, 17*(2), 256-281. https://doi.org/10.1108/JRIT-03-2024-0052

Ezzaim, A., Dahbi, A., Aqqal, A., & Haidine, A. (2025). AI-based learning style detection in adaptive learning systems: A systematic literature review. *Journal of Computers in Education, 12*, 731–769. https://doi.org/10.1007/s40692-024-00328-9

Flores, M., Ramírez, L., & Hernández, J. (2023). Rethinking virtual laboratories: From procedural simulation to active learning environments. *Computers & Education, 190*, 104605.

González, M., & Méndez, J. (2021). Pedagogical challenges in the design of virtual laboratories in higher education. *International Journal of Educational Technology in Higher Education, 18*(1), 1–15.

Harris, D. J., Bird, J. M., Smart, P. A., Wilson, M. R., & Vine, S. J. (2020). A framework for the testing and validation of simulated environments in experimentation and training. *Frontiers in Psychology, 11*, 605. https://doi.org/10.3389/fpsyg.2020.00605

Hernández, R., Pérez, M., & López, J. (2020). Technological infrastructure challenges for the implementation of virtual laboratories in higher education. *Education and Information Technologies, 25*(6), 5023–5040.

Hsu, H.-Y., Bowden, D., & Acosta, S. T. (2025). The relations among students' digital accessibility, digital competence, self-efficacy for self-direction in learning and self-rated performance in engineering virtual laboratories. *Journal for STEM Education Research, 8*(2), 283-302. https://doi.org/10.1007/s41979-024-00130-3

Hu-Au, E., & Okita, S. (2021). Exploring differences in student learning and behavior between real-life and virtual reality chemistry laboratories. *Journal of Science Education and Technology, 30*(6), 862-876. https://doi.org/10.1007/s10956-021-09925-0

Jallad, S. T., & Işık, B. (2025). The effectiveness of immersive virtual reality simulation as an innovative learning strategy for acquisition of clinical skills in nursing education: Experimental design. *Games for Health Journal, 14*(2), 110-118. https://doi.org/10.1089/g4h.2023.0139

Kapilan, N., Vidhya, P., & Gao, X.-Z. (2021). Virtual laboratory: A boon to the mechanical engineering education during COVID-19 pandemic. *Higher Education for the Future, 8*(1), 31-46. https://doi.org/10.1177/2347631120970757

Kenny, J., & Fluck, A. E. (2022). Emerging principles for the allocation of academic work in universities. *Higher Education, 83*(6), 1371-1388. https://doi.org/10.1007/s10734-021-00747-y

Khahro, S. H., Shaikh, H. H., Zainun, N. Y., Sultan, B., & Khahro, Q. H. (2023). Delay in decision-making affecting construction projects: A sustainable decision-making model for mega projects. *Sustainability, 15*(7), 5872. https://doi.org/10.3390/su15075872

Klami, A., Damoulas, T., Engkvist, O., Rinke, P., & Kaski, S. (2024). Virtual laboratories: Transforming research with AI. *Data-Centric Engineering, 5*, e19. https://doi.org/10.1017/dce.2024.15

Kolil, V. K., & Achuthan, K. (2024). Virtual labs in chemistry education: A novel approach for increasing student's laboratory educational consciousness and skills. *Education and Information Technologies, 29*(18), 25307-25331. https://doi.org/10.1007/s10639-024-12858-x

Li, J., & Liang, W. (2024). Effectiveness of virtual laboratory in engineering education: A meta-analysis. *PLoS One, 19*(12), e0316269. https://doi.org/10.1371/journal.pone.0316269

Lin, Y., Wang, S., & Lan, Y. (2022). The study of virtual reality adaptive learning method based on learning style model. *Computer Applications in Engineering Education, 30*(2), 396-414. https://doi.org/10.1002/cae.22462

Machwate, S., Bendaoud, R., Henze, J., Berrada, K., & Burgos, D. (2021). Virtual exchange to develop cultural, language, and digital competencies. *Sustainability, 13*(11), 5926. https://doi.org/10.3390/su13115926

Marks, B., & Thomas, J. (2022). Adoption of virtual reality technology in higher education: An evaluation of five teaching semesters in a purpose-designed laboratory. *Education and Information Technologies, 27*(1), 1287-1305. https://doi.org/10.1007/s10639-021-10653-6

Marzi, G., Balzano, M., Caputo, A., & Pellegrini, M. M. (2025). Guidelines for bibliometric-systematic literature reviews: 10 steps to combine analysis, synthesis and theory development. *International Journal of Management Reviews*, *27*(1), 81-103. https://doi.org/10.1111/ijmr.12381

Miller, V. A., Marks, T., & Thompson, D. K. (2025). Student performance and perceptions in a hybrid laboratory model: An exploratory study of interactive virtual simulations and in-person integration in a foundational microbiology course. *Journal of Microbiology & Biology Education*, *26*(1), e00203-00224. https://doi.org/10.1128/jmbe.00203-24

Nakata, Y., Sato, K., Tanaka, M., & Yamamoto, H. (2024). The future of virtual laboratories in STEM education: Lessons learned from the COVID-19 pandemic. *Computers & Education: Artificial Intelligence*, *5*, 100143.

Ni, J.-L., Li, J.-R., Xu, D.-J., Yu, Y.-P., & Wang, Q.-H. (2022). A development platform prototype for virtual laboratories. *Computer Applications in Engineering Education*, *30*(3), 678-689. https://doi.org/10.1002/cae.22480

Poo, M. C.-P., Lau, Y.-Y., & Chen, Q. (2023). Are virtual laboratories and remote laboratories enhancing the quality of sustainability education? *Education Sciences*, *13*(11), 1110. https://doi.org/10.3390/educsci13111110

Qawaqneh, H., Ahmad, F. B., & Alawamreh, A. R. (2023). The impact of artificial intelligence-based virtual laboratories on developing students' motivation towards learning mathematics. *International Journal of Emerging Technologies in Learning*, *18*(14), 105–121. https://doi.org/10.3991/ijet.v18i14.39873

Qiao, J., Xu, J., Li, L., & Ouyang, Y.-Q. (2021). The integration of immersive virtual reality simulation in interprofessional education: A scoping review. *Nurse Education Today*, *98*, 104773. https://doi.org/10.1016/j.nedt.2021.104773

Reeves, S. M., & Crippen, K. J. (2021). Virtual laboratories in undergraduate science and engineering courses: A systematic review, 2009–2019. *Journal of Science Education and Technology*, *30*(1), 16-30. https://doi.org/10.1007/s10956-020-09866-0

Ruiz, J., & Caballero, A. (2023). Hybrid laboratory models in higher education: Prospects, challenges, and post-pandemic transformations. *Journal of Computer Assisted Learning*, *39*(4), 1123–1137.

Sembey, R., Hoda, R., & Grundy, J. (2024). Emerging technologies in higher education assessment and feedback practices: A systematic literature review. *Journal of Systems and Software*, *211*, 111988. https://doi.org/10.1016/j.jss.2024.111988

Shurygin, V., Ryskaliyeva, R., Dolzhich, E., Dmitrichenkova, S., & Ilyin, A. (2022). RETRACTED ARTICLE: Transformation of teacher training in a rapidly evolving digital environment. *Education and Information Technologies*, *27*(3), 3361-3380. https://doi.org/10.1007/s10639-021-10749-z

Silva, A., & Romero, C. (2022). Digital infrastructure and institutional readiness for virtual laboratories in universities. *Computers & Education*, *176*, 104353.

Singh, G., Mantri, A., Sharma, O., & Kaur, R. (2021). Virtual reality learning environment for enhancing electronics engineering laboratory experience. *Computer Applications in Engineering Education*, *29*(1), 229-243. https://doi.org/10.1002/cae.22333

Tauber, A. L., Levonis, S. M., & Schweiker, S. S. (2022). Gamified virtual laboratory experience for in-person and distance students. *Journal of Chemical Education*, *99*(3), 1183-1189. https://doi.org/10.1021/acs.jchemed.1c00642

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Wang, J., Li, Y., Chen, X., & Wang, C. (2025). Before and after: How did the pandemic reshape virtual laboratory research? *SAGE Open*, *15*(2), 21582440251339961. https://doi.org/10.1177/21582440251339961

Williamson, B. (2020). New digital laboratories of experimental knowledge production: Artificial intelligence and education research. *London Review of Education*, *18*(2), 209-220. https://doi.org/10.14324/LRE.18.2.05

Wu, W.-C. V., Manabe, K., Marek, M. W., & Shu, Y. (2023). Enhancing 21st-century competencies via virtual reality digital content creation. *Journal of Research on Technology in Education*, *55*(3), 388-410. https://doi.org/10.1080/15391523.2021.1962455

Yuan, C.-H., & Wu, Y. J. (2020). Mobile instant messaging or face-to-face? Group interactions in cooperative simulations. *Computers in Human Behavior*, *113*, 106508. https://doi.org/10.1016/j.chb.2020.106508

Zhang, N., & Liu, Y. (2024). Design and implementation of virtual laboratories for higher education sustainability: A case study of Nankai University. *Frontiers in Education*, *8*, 1322263. https://doi.org/10.3389/feduc.2023.1322263

Zhang, Y., Yang, Y., Chu, Y., Sun, D., Xu, J., & Zheng, Y. (2024). Virtual laboratories in science education: Unveiling trajectories, themes, and emerging paradigms (2013-2023). *Journal of Baltic Science Education*, *23*(5), 990-1009. https://doi.org/10.33225/jbse/24.23.990