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Development of interactive virtual laboratories for distance learning in natural sciences

Desarrollo de laboratorios virtuales interactivos para el aprendizaje a distancia en ciencias naturales

Valentyna Kolodii
Candidate of Biological Sciences (Ph.D.), Senior Instructor, Department of Biology and Ecology, Faculty of Natural Sciences and Economics, Kamianets-Podilskyi Ivan Ohiienko National University, Kamianets-Podilskyi, Ukraine.
https://orcid.org/0000-0002-9669-4144
kolodiyva@ukr.net
Inna Koreneva
Doctor of Pedagogical Sciences, Professor, Professor of the Department of Theory and Methods of Teaching Natural Sciences, Faculty of Natural Sciences and Physical-Mathematical Education, Oleksandr Dovzhenko Hlukhiv National Pedagogical University, Hlukhiv, Ukraine.
https://orcid.org/0000-0002-1117-7624
i.koreneva74@gmail.com
Nataliia Prokopenko
PhD in Biology, Associate Professor of the Department of Ecology, Road-Building Faculty, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine.
https://orcid.org/0000-0002-2783-2777
natvikpro08@gmail.com
Oksana Huda
Candidate of Technical Sciences, Associate Professor of Higher Mathematics, Department of Physics and Higher Mathematics, Faculty of Transport and Mechanical Engineering, Lutsk National Technical University, Lutsk, Ukraine.
https://orcid.org/0000-0002-3602-7892
gudaoksana@lutsk-ntu.com.ua
Yuliia Shaforost
PhD in Chemical Sciences, Associate Professor, Head of the Department of Chemistry and Nanomaterials, Educational and Scientific Institute of Natural and Agrarian Sciences, Bohdan Khmelnytsky Cherkasy National University, Cherkasy, Ukraine.
https://orcid.org/0000-0002-0002-2803
ZdorYulia@ukr.net

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Abstract

The research investigates the existing interactive virtual laboratories used in distance learning in natural sciences, focusing on their functions, potentials, and limitations. To achieve this, a descriptive research design was employed, involving a comprehensive review of recent scientific publications, methodological resources, and institutional documentation related to the use of virtual laboratories within the educational process. The selected platforms were analyzed for their effectiveness in facilitating remote science education through interactive experiments, simulation of scientific phenomena, and visualization of complex concepts in biology, chemistry, and physics disciplines. Key features identified across all platforms include high interactivity, gamification elements, accuracy, and adaptability to users' needs. The study also established criteria to assess the educational efficiency of these tools. A comparative analysis revealed the advantages (engagement, flexibility, and conceptual clarity) and the challenges, including technical limitations and the need for pedagogical assistance in distance learning in natural sciences. As a result, the research proposes specific organizational and instructional recommendations to support the effective implementation of virtual laboratories. The outcomes are particularly relevant for higher education institutions aiming to enhance the professional preparation of future specialists in natural sciences, particularly during crises when distance learning is more applicable.

Keywords: digital tools for education, distance learning, interactive virtual laboratories, natural sciences, simulation.

Resumen

La investigación analiza los laboratorios virtuales interactivos existentes utilizados en el aprendizaje a distancia en las ciencias naturales, centrándose en sus funciones, potencialidades y limitaciones. Para ello, se empleó un diseño de investigación descriptivo que incluyó una revisión exhaustiva de publicaciones científicas recientes, recursos metodológicos y documentación institucional relacionada con el uso de laboratorios virtuales en el proceso educativo. Las plataformas seleccionadas fueron analizadas en cuanto a su eficacia para facilitar la educación científica a distancia mediante experimentos interactivos, simulaciones de fenómenos científicos y visualización de conceptos complejos en las disciplinas de biología, química y física. Entre las características clave identificadas en todas las plataformas se encuentran la alta interactividad, elementos de gamificación, precisión y adaptabilidad a las necesidades de los usuarios. El estudio también estableció criterios para evaluar la eficiencia educativa de estas herramientas. Un análisis comparativo reveló ventajas como la motivación, flexibilidad y claridad conceptual, así como desafíos, entre ellos limitaciones técnicas y la necesidad de asistencia pedagógica en el aprendizaje a distancia en ciencias naturales. Como resultado, la investigación propone recomendaciones organizativas y didácticas específicas para apoyar la implementación efectiva de laboratorios virtuales. Los resultados son particularmente relevantes para las instituciones de educación superior que buscan mejorar la formación profesional de futuros especialistas en ciencias naturales, especialmente en contextos de crisis donde el aprendizaje a distancia se vuelve más necesario.

Palabras clave: herramientas digitales para la educación, aprendizaje a distancia, laboratorios virtuales interactivos, ciencias naturales, simulación.

Introduction

In response to the challenges posed by the COVID-19 pandemic and the full-scale Russian aggression in Ukraine, institutions of higher education were forced to suspend in-person classes and transition to distance learning. However, it soon became evident that traditional distance education—delivered primarily through video conferencing platforms—often lacks opportunities for practical experimentation. This mode of instruction typically relies on digitized resources or institutionally prepared materials, such as pre-recorded lectures, pre-designed group discussions, and problem-solving exercises.

Research has shown that virtual laboratories, which employ virtual simulations, offer conditions conducive to engaging with complex procedures and repeating experiments to enhance professional competencies (Serrano-Perez et al., 2021). Moreover, several scholars argue that effective content development—particularly in virtual laboratory settings—is essential for successful learning in the natural sciences (Hassan et al., 2022). According to Bati, Teslenko, Yuryk, Avtomieienko, and Bashkirova (2024), virtual laboratories in science education help bridge conceptual understanding and practical application. High-quality virtual lab content is interactive, scientifically accurate, and aligned with educational objectives. Well-structured digital materials are designed to foster the development of practical skills and support effective learning outcomes. Additionally, they contribute to creating a more accessible educational environment.

Under such conditions, laboratory experience and demonstrations prevent students from developing essential skills, including problem-solving, data analysis, technical competence, digital literacy, and critical thinking (Hulai et al., 2024). Additionally, many scientific works focus on the importance of using digital technologies for the formation of critical thinking, data literacy, problem-solving, and digital competence (Gonzalez-Mohino et al., 2023). As demonstrated in recent research (Kurebay et al., 2023), the development of digital competence among future specialists is a key factor in the successful implementation of online learning tools, including IVLs. Without access to interactive learning tools, future specialists have serious difficulties in understanding complex scientific notions and mechanisms that affect the subject or topic comprehension and further complicate the formation of professional competence among students. Donelan and Kear (2023) add that students should learn to work within a virtual team since this ability has become central to most industries. Such work also requires consideration of intercultural communication competencies (Turabay et al., 2023). At the same time, cognitive offloading may take place when students delegate cognitive tasks to external aids and do not engage in reflective thinking (Gerlich, 2025). To compare traditional and innovative tools, some scholars (Sipii et al., 2024) insist that the development of soft skills highlights the need for interactive tools like virtual laboratories that promote collaboration, problem-solving, and adaptability.

Laboratory learning brings new technological advances to support the educational process at the institution of higher education (Zhang & Liu, 2023). Scholars insist that virtual experiments can efficiently supplement traditional experimental teaching. It was found that virtual experimentation enriches teaching content and creates interactive, simulation-based environments where students can conduct experiments remotely. Virtual laboratories are presently used to train future specialists in different fields, including healthcare workers (Tsekhmister et al., 2023) and engineers (Li & Liang, 2024). Some works stress the advantages of using virtual laboratories while teaching natural sciences, particularly chemistry (Hulai et al., 2024), physics (El Kharki et al., 2021; Shamshin, 2021), biology (Kikari et al., 2024), or environmental sciences (Ron-Valenzuela et al., 2022). Usually, the recent findings concern the pedagogical effect of using virtual laboratories in the educational process. For example, some works describe that digital platforms can replicate real-life laboratory settings so students can manipulate equipment, observe the experiment, and analyze its outcomes (El Kharki et al., 2021; Li & Liang, 2024). Virtual laboratories direct students' attention (Raman et al., 2022), enabling a more engaging learning environment (LE) and implementing the practical approach to distance learning in natural sciences (Hulai et al., 2024).

At the same time, despite several works in the field, it was found that the development of interactive virtual laboratories (IVLs) for distance learning in natural sciences is essential for the scientific discourse due to its transformative impact on education. Since these virtual laboratories provide students with practical experience in the immersive digital LE, they offer accessibility and flexibility and become a highly valuable tool for remote learners. This study offers new ideas about virtual laboratories' functions and potential; it focuses on the efficiency criteria of these laboratories to ensure educational quality. Besides, the study presents the advantages and disadvantages of using virtual laboratories within the educational process that may help integrate them into the natural sciences curriculum.

Taking this into consideration, the research aim is to describe the existing IVLs, as well as their functions, potentials, and limitations in the context of distance learning in natural sciences. The research objectives concern the following: (1) to analyze modern virtual laboratories and their characteristics; (2) to determine the criteria of efficiency of such laboratories; and (3) to reveal the advantages and disadvantages of interactive decisions in comparison with traditional teaching methods.

Literature Review

Currently, virtual laboratories prepare students to recognize the laboratory environment before engaging in actual conditions and overcome the problems faced in traditional classes during experiments (Sapriati et al., 2023). Initially, the virtual laboratory concept emerged as a response to the limitations of traditional laboratory settings, such as the high costs of equipment and materials (Ron-Valenzuela et al., 2022). In the 1990s, early virtual laboratory versions began appearing in universities and research institutions. These laboratories worked as simulators of basic scientific experiments to complement traditional classroom teaching methods (Li & Liang, 2024). In the 2000s, more sophisticated software was developed to fuel virtual laboratories' growth (Hassan et al., 2022). The rapid advancement of interactive multimedia, 3D graphics, and simulation tools contributed to the introduction of IVLs. Here, it is worth explaining the definition of Sellberg, Nazari, and Solberg (2024), stating that virtual laboratories are technology-mediated learning contexts within 2D desktop-based simulations or 3D virtual reality (VR) environments consisting of head-mounted displays.

Notably, during the COVID-19 pandemic and military conflicts, virtual laboratories became essential since they could ensure the continuity of education despite the restrictions on physical laboratory access. In this context, Matviichuk, Ferilli, and Hnedko (2022) indicate that distance learning provides the only opportunity to organize comfortable conditions for learning when the country is at war and when the educational process has been dusrupted. Other findings insist that in times of war the introduction of virtual laboratories within the educational process help students manage anxiety caused by conflict, provide a cognitive escape, and maintain motivation in the LE (Mayer et al., 2023).

Universities began incorporating virtual laboratories into their curricula as supplementary tools to traditional laboratory learning. Today, these labs are integrated into many educational systems worldwide, increasing the possibilities of learning-by-doing approaches (El Kharki et al., 2021). A historical review and bibliometric analysis of Raman et al. (2022) found that the institutions where virtual laboratories are widely implemented are in the developed economies of Spain, Germany, and the United States. Other countries include Germany, China, Austria, Netherlands, Switzerland, Brazil, and Indonesia. The scholars indicate that the European countries lead the research on virtual laboratories in higher education, and they demonstrate a much smaller number of works from Asian and African countries. In this context, it is essential to mention the research on the design and implementation of virtual laboratories in Chinese universities (Zhang & Liu, 2023), the improvement of students' self-regulated learning through virtual laboratory technology (Sapriati et al., 2023), and the evaluation of the influence of the virtual laboratory on the students' success rate (Aliev et al., 2024).

The problems of using virtual laboratories for distance learning at higher education institutions have often become research topics among Ukrainian investigators. For example, Tiahunova & Lavryk (2023) describe a virtual laboratory as an effective tool for organizing effective distance learning. They insist virtual laboratories allow students to receive quality education during a crisis. Some works conduct a comparative analysis of various computer simulation programs (Shamshin, 2021). Other scholars (Lucenko et al., 2023) outlined the formation of digital competence using laboratory tasks. Special attention was paid to using virtual technologies in inclusive education to meet diverse learning needs (Iskakova, 2023; Hudym et al., 2024).

The study of the development of interactive virtual laboratories (IVLs) requires a thorough analysis of the topic's theoretical foundations. According to Kok et al. (2021), a virtual laboratory fosters a constructivist learning environment by promoting active student participation and individual responsibility in the construction of new knowledge. Recent studies have explored the cognitive approach to implementing virtual laboratories in distance education (Elkin et al., 2024; Wen et al., 2024), emphasizing that learning materials should be designed according to cognitive theory. This is because virtual laboratory technologies help reduce students' cognitive load and enhance learning outcomes.

Gamification is also identified as a core principle in the implementation of virtual laboratories (Vahdatikhaki et al., 2023). Additionally, Shamshin (2021) provides a detailed analysis of the advantages of virtual laboratory work in physics. The author highlights benefits such as unrestricted access, training flexibility, development of skills related to computer technologies, equal learning opportunities, and enhanced visualization through realistic virtual lab environments.

Simanca et al. (2024) explained the ethics of the application of virtual laboratories within the educational process. Moreover, they describe a virtual laboratory as an effective instrument to assess the effectiveness of practical lessons if they are implemneted within the educational process in accordance with methodological guidelines and on conditions that instructors possess high level of digital competence.

Moreover, some studies focus on using different concepts regarding virtual laboratories. It was found that VR technology enhances practical learning through immersive and interactive simulations (Vahdatikhaki et al., 2023). At the same time, augmented reality (AR) provides a training scenario for teaching natural sciences subjects and helps personalize the educational process (Södervik et al., 2021). AR/VR significantly changes the teaching and learning paradigm, improving students' performance and allowing them to apply theoretical knowledge in a practical, real-life context (Zhao et al., 2023). Artificial intelligence (AI) based virtual laboratories are essential for developing students' motivation towards learning (Qawaqneh et al., 2023). According to Klami et al. (2024), AI tools also contribute to preparing students for autonomous experiments. To add, integrating AI technologies into interactive virtual laboratories can provide personalized learning experiences and real-time feedback, thereby improving student engagement and competency in natural sciences (Bashkirova et al., 2024).

Regarding the development of a virtual laboratory, adaptive LE means the intelligent and dynamic customization of learning content and activities to meet the student's needs (Gligorea et al., 2023). It is considered that adaptive LE supports students in tailoring educational content, instructional strategies, and assessment instruments. Elmoazen et al. (2023) concentrated their scientific efforts on the evaluation of effective learning strategies and the sequence of virtual laboratory activities. They emphasized that the use of AI-based tools in virtual laboratory supports instructional, identifies at-risk students to provide effective interventions, help develop personalized learning materials, and assess students' outcomes.

Also, the literature review revealed the leading platforms applied for IVLs. For example, Physics Education Technology (PhET) provides visualizations and teaching aids that help students understand content knowledge (Banda & Nzabahimana, 2022). In comparison, the Labster platform creates virtual laboratory simulations in the natural sciences. More than 400 simulations have been developed in biology, chemistry, physics and other related disciplines (Hulai et al., 2024). Virtual Labs software (VLabs) supports distance or remote learning by creating simulated learning environments (Reginald, 2023). In addition, VLabs has the potential to include AI systems to monitor and give individualized feedback. The algorithm of virtual microscoping experiment was described in the study of Sypsas & Kalles (2023). Certain works (Chen, 2020; Tsirulnikov et al., 2023) were devoted to the introduction of gamified virtual laboratory. It is worth mentioning that some authors (Sanzana et al., 2023) confirm that gamified virtual laboratories increase students' involvement and they are considered a potentially suitable pedagogical tool for low-risk interactive learning.

The critical analysis of scientific sources in the field proves that the article seeks to bridge the gap between extensive theoretical findings and practical approaches from methodical reports, institution directives, and reviews outlining the fundamental implementation strategies. The study offers solutions for the practical usage of IVLs within the educational process to maximize their pedagogical potential.

Methodology

This study on the development of IVLs for distance learning in natural sciences is based on descriptive research design. It focuses on analyzing the existing scientific resources and theory frameworks representing the conceptual system of guidance, rules, and principles for understanding the research problem. Notably, the non-experimental approach examines various aspects regarding developing an interactive virtual laboratory without manipulating variables and drawing a comprehensive overview of today's practices and innovations in the field.

Firstly, the research analyzes scientific literature using academic databases such as Scopus, Web of Science, ERIC, and Google Scholar. The search included publications from January 2019 to March 2024 to ensure the inclusion of the most recent and relevant studies. The following keywords and Boolean operators were used: "interactive virtual laboratory" AND "distance learning", "virtual labs" AND "natural sciences", "online laboratory learning" AND "science education" OR "STEM". Additionally, the reference chaining method was applied to identify further relevant studies from the reference lists of selected papers. Secondly, the methodological documents and institutional guidelines were used to establish the policies on quality in teaching, learning, and assessment in the LE, where an interactive virtual laboratory is introduced. Thirdly, the study was based on expert reviews evaluating the efficiency of IVLs within the educational process. Fourthly, technical reports and user reviews were analyzed; they gave information on the implementation of IVLs for distance learning and the technical characteristics of interactive virtual laboratory equipment. These sources examined the best practices, technological advancements, and pedagogical strategies for IVLs.

When selecting the scientific sources, the following inclusion criteria were considered: (1) sources should be peer-reviewed journal articles, conference proceedings, monographs, and policy documents; (2) they should focus on the development, use, or evaluation of IVLs in natural sciences education; (3) they are studies discussing IVLs in the context of distance or online learning; (4) publications should be in English or Ukrainian. At the same time, certain exclusion criteria were included: (1) studies unrelated to virtual laboratories or not situated in educational contexts; (2) publications lacking methodological transparency or theoretical grounding; (3) articles published before 2019. Importantly, the selection process was documented and reviewed by two independent experts to ensure reliability and avoid selection bias. As a result, all selected sources were critically evaluated from the point of view of relevance to the research topic; scientific accuracy, based on the clarity of research design and findings; practical applicability to the implementation of IVLs in current educational environment; technological depth; and pedagogical value.

Official methodological documents and institutional guidelines related to the integration of digital technologies in science education were analyzed to identify national and international policies on quality teaching, learning, and assessment. This provided a framework for understanding how IVLs enhance educational quality in different educational environments. To enhance the reliability of findings, expert opinions from instructional designers and science educators involved in IVL development were reviewed. Technical reports and user feedback were collected from public platforms and academic case studies to assess the real-world implementation, usability, and scalability of IVL systems. Figure 1 analyzes the sources selected for the research.

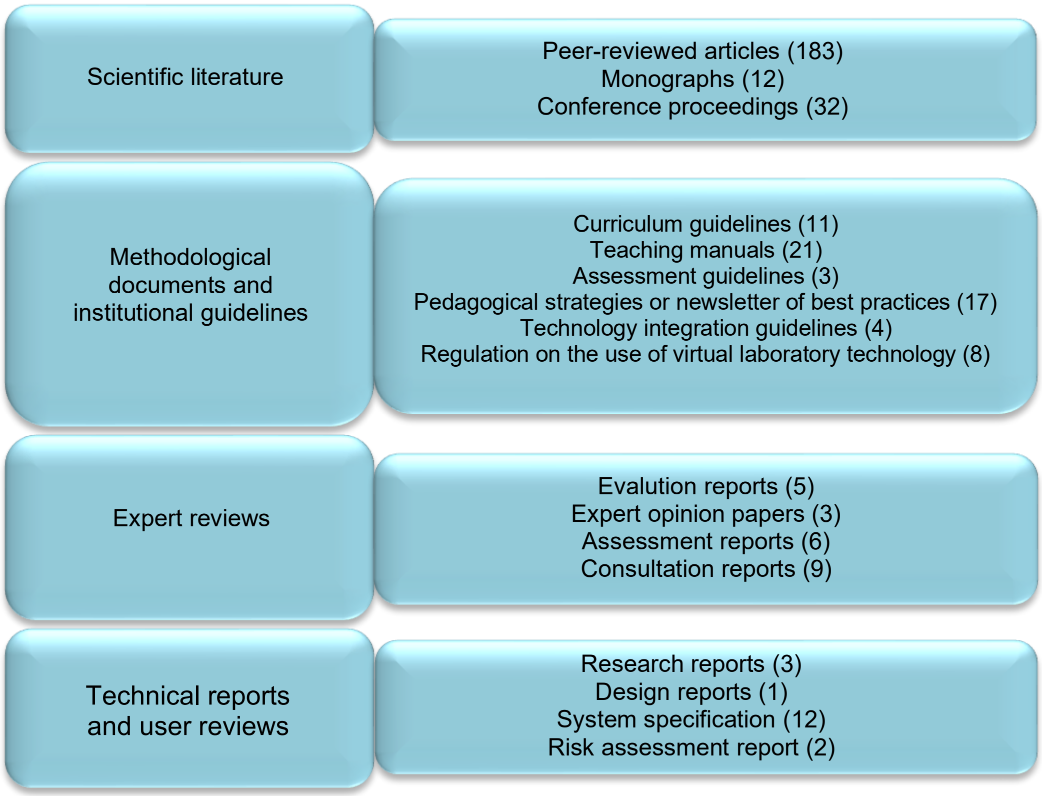

Figure 1. The analysis of sources selected for the research.
Source: author's development.

During the research, documents and scientific literature were analyzed, and comparative analysis was used. These methods contributed to deeply examining the research problems and ensured the objective investigation of concepts and trends related to IVLs and distance learning. Notably, the analysis of documents and scientific literature facilitated the comprehensive understanding of the research subject and further recognized the areas requiring detailed exploration. In addition, this method provided a theoretical foundation for the research and contextualized the new findings. The comparative analysis evaluated different interactive virtual laboratory models implemented in various LEs. Also, a comparative analysis was introduced to compare different platforms and tools used for IVLs and assess the design and functionality of IVLs from different institutions based on methodical documents and guidelines. The method was also used to evaluate pedagogical approaches to the implementation of IVLs and to analyze the effectiveness of the technology in distance learning. Both methods – analysis of documents and scientific literature and comparative analysis – suggested recommendations for improving the educational process to enhance students' virtual learning experiences in natural sciences.

At the same time, the research brings some limitations regarding the absence of empirical experiments and possible subjective interpretation of the efficiency of IVLs for distance learning. However, these limitations do not undermine the overall validity or significance of the study since they provide an opportunity to concentrate on the research relevance, topicality, and applicability.

Results

The findings showed that six leading platforms are applied for IVLs in distance learning in natural sciences. They include PhET, Labster, VLabs, eScience Labs, Molecular Workbench, and Simulab. The detailed analysis of these platforms, including their characteristics and expected skills or competencies to be formed, is presented in Table 1. Summarizing the findings, the authors found that the platforms applied for IVLs share several similar features, making them effective instruments for distance learning in natural sciences. Firstly, all these platforms enable practical, interactive experiments and visualize complex scientific concepts. Secondly, all IVLs support distance learning. Thirdly, these laboratories can incorporate gamified elements, and students are encouraged to participate actively in the educational process. Fourthly, most platforms like Moodle or Canvas can integrate with learning management systems (LMS). Fifthly, some platforms (e.g., Labster and SimuLab) include real-life exercises and industry-relevant training activities to enhance professional competence among students. At the same time, PhET, Labster, VLabs, eScience Labs, Molecular Workbench, and Simulab possess specific differences that suggest using them in different LEs. For example, PhET visualizes basic scientific concepts, while Labster provides VR-based laboratory training. VLabs focuses on realistic virtual laboratory simulations.

In contrast, eScience Labs combines physical laboratory equipment with various digital elements. Molecular Workbench specializes in molecular and atomic-level simulations, and Simulab aims to train future medical and healthcare specialists. Still, it can often be applied to teach medical or biological concepts to students of different specialties. Considering this, all six IVLs are valuable tools for modern natural sciences education in the context of distance learning.

Table 1.
Modern IVLs or platforms and their characteristics

Laboratory/ Platform	Characteristics	Subjects	Expected skills and competences
PhET	creates interactive simulations for various scientific concepts; visualizes the experiment results in real-time	Physics, chemistry, biology, earth science	Conceptual understanding, critical thinking, problem-solving, logical thinking, digital literacy, engagement, and motivation
Labster	supports virtual experiments through realistic graphics and interactive content; provides adaptive learning tools; integrates assessment and feedback instruments	Biology, microbiology, chemistry, and physics	Logical reasoning, decision-making, technical skills, data analysis, digital literacy, teamwork, biological and chemical understanding, adaptability, and self-paced learning
VLabs	gives remote access to lab activities	Physics, engineering, and chemistry	Experimental skills, problem-solving, data analysis, technical skills, critical thinking, communication, and independent learning
eScience Labs	Creates experiment learning through the incorporation of real-time data and analysis tools	Biology, microbiology, chemistry, and environmental science	Practical laboratory skills, critical thinking, decision-making, digital literacy, technical competence, communication, and time management
Molecular Workbench	visualizes molecular and atomic structures; provides interactive 2D and 3D simulations; uses biotechnologies in distance education	Biology, chemistry, and physics	Dynamic modeling and simulation skills, computational thinking, interdisciplinary problem solving, virtual experimentation, reasoning, and adaptive learning
Simulab	offers virtual simulations; develops real-life laboratory exercises; includes tools for performing complex procedures in a virtual medical laboratory	Healthcare and medicine	Scientific and laboratory skills, critical thinking, problem-solving, data analysis, technical competence, digital literacy, predictive thinking, and medical and engineering-specific skills

Source: author's development.

The criteria of efficiency of IVLs in distance learning were studied in two dimensions: (1) based on the analysis of scientific literature and (2) methodical documents, institutional guidelines and reviews. The findings from the systematic analysis revealed that the majority of sources (76.5% of scientific articles and 78.6% of other documents) identify accuracy as a key efficiency criterion for IVLs. This refers to the requirement that all learning materials used in experimental training present scientifically valid, objective, and up-to-date information. 54.5% of scientific articles and 63.2% of documents emphasize interactivity, understood as the ability of IVLs to include dynamic and engaging exercises that enhance student participation.

Other criteria relate to accessibility (the possibility for all students to use it independently), modeling (the ability to simulate real-life activities), adaptability to users (the ability of platforms to personalize learning materials according to students' needs and preferences), cost-effectiveness (the lower price of digital platforms in comparison to physical laboratory equipment), the possibility of incorporation of assessment and feedback tools within interactive virtual laboratory platform, and alignment with curriculum meaning that educational activities are aimed at the formation of professional skills of students.

Additional efficiency criteria frequently referenced include accessibility (ensuring all students can independently access and use the IVLs), modeling capacity (the ability to simulate real-life scientific processes), user adaptability (personalization of content based on students' needs), cost-effectiveness (lower operational costs compared to physical laboratories), assessment integration (the inclusion of built-in feedback and evaluation tools), and curriculum alignment (the extent to which IVL activities support the development of professional competencies aligned with educational standards). These criteria were further verified by a panel of experts involved in the research. These experts reviewed the findings derived from the systematic literature and document analysis and confirmed the relevance, clarity, and applicability of the proposed criteria. Their verification adds confidence in the conceptual framework. Also, it supported its validity as a foundation for future empirical research. Figure 2 refers to the analysis of the criteria of efficiency of IVLs in distance learning in natural sciences.

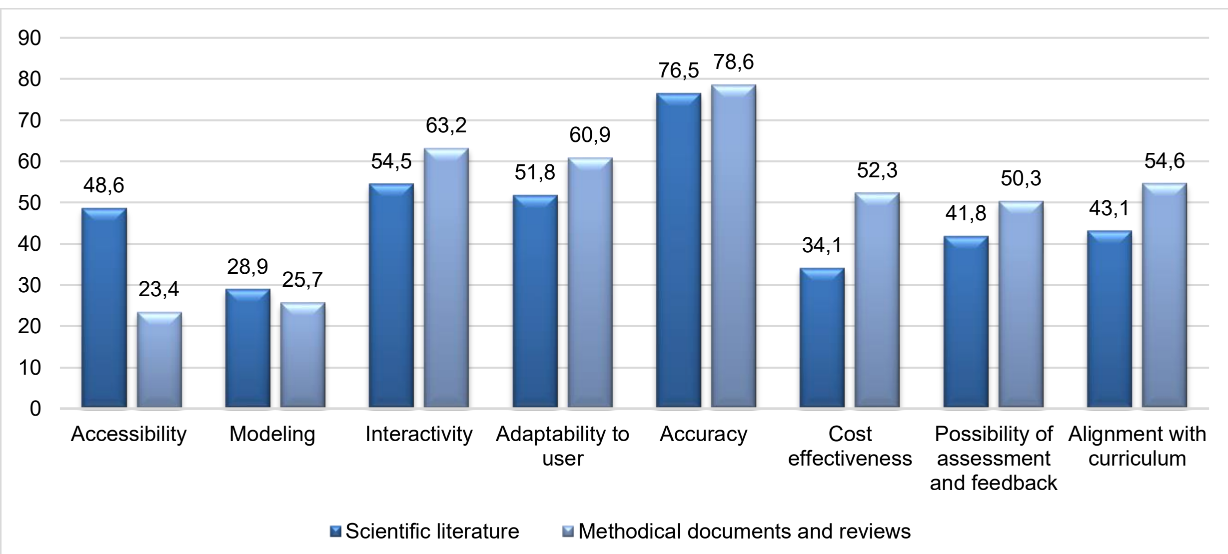

Figure 2. The criteria of efficiency of IVLs in distance learning.
Source: author's development.

Table 2 analyses the efficiency of IVLs in distance learning in natural sciences. "+" means the criterion was mentioned in the scientific articles and/or methodical documents. "-" refers to the fact that the criterion does not belong to the interactive virtual laboratory. According to the findings, all virtual laboratories and platforms are characterized by interactivity, modeling, user adaptability, and accuracy. At the same time, VLabs, eScience Labs, Molecular Workbench, and Simulab are not accessible to all learners since they are designed for specific categories of students or levels of training. Labster, eScience Labs, and Simulab are not entirely cost-effective because they contain subscribed or paid content and cannot be used freely. PhET, VLabs, and Molecular Workbench do not contain assessment and feedback tools that make evaluating students' learning outcomes difficult. Besides, Molecular Workbench has preliminary development content and sometimes may not align with the curriculum.

Table 2.
Analysis of efficiency of IVLs or platforms used in distance learning

Criteria of efficiency	Laboratory/Platform					
	PhET	Labster	VLabs	eScience Labs	Molecular Workbench	Simulab
Accessibility	+	+	-	-	-	-
Modeling	+	+	+	+	+	+
Interactivity	+	+	+	+	+	+
Adaptability to users	+	+	+	+	+	+
Accuracy	+	+	+	+	+	+
Cost-effectiveness	+	-	+	-	+	-
Assessment and feedback	-	+	-	+	-	+
Alignment with Curriculum	+	+	+	+	-	+

Source: author's own development.

This analysis proves that IVLs contribute significantly to the effectiveness of LE despite some of them not fully meeting the efficiency criteria. Further, the research focused on evaluating the advantages and challenges of IVLs. Special attention was paid to the strengths and weaknesses of IVLs in the context of distance learning in natural sciences. The findings showed that all six platforms have certain advantages and challenges in the educational process. Table 3 presents a detailed examination of the advantages and challenges of virtual laboratories/platforms used in distance learning. However, the scientific literature and methodical documents prove that interactive virtual laboratories are integral to the LE, particularly during a crisis when the traditional classrooms are inaccessible.

Table 3.
Advantages and challenges of virtual laboratories/platforms used in distance learning

Laboratory/ Platform	Advantages	Number of sources (%)	Challenges	Number of sources (%)
PhET	Is widely available to students and educators	67,8	Is not appropriate for advanced research	23,4
	Provides engaging, practical simulations	69,2	Does not include formal assessment tools	59,0
	Covers a wide range of natural sciences subjects	54,3	Lacks real-life experimentation	35,5
	Contains an easy interface	35,6		
	Is used for different educational levels.	42,1	Depends on the Internet	70,2
	Encourages students to explore concepts through trial and error	48,2	Has limited adaptability	19,4
	Fosters critical thinking and problem-solving skills	66,9		
Labster	Possesses high-quality 3D simulations	72,3	Has a high cost for the institutions	45,3
	Aligns with the curriculum;	80,4		

	uses interactive elements, virtual scenarios, and game-based activities	68,4	Requires stable Internet.	12,3
	Is available online.	89,9	Cannot fully replace manual skills	11,9
	Provides different levels of difficulty	56,3		
	Includes assessment and feedback tools	63,1	Requires advanced hardware	9,4
	Is safe	47,8		
VLabs	Allows to conduct experiments remotely	56,9	Lacks practical skills	23,6
	Reduces expenses related to laboratory equipment	67,4	Limits face-to-face interaction	34,7
	Creates a risk-free LE	43,1		
	Is repeatable	23,7	Has difficulties in the evaluation of practical skills	32,0
	Enables self-paced learning	33,9		
	Can be used for many students	29,3		
	Provides automated assessments	17,8		
eScience Labs	Includes interactive simulations	78,3	Provides fixed experiments	12,9
	Offers flexible scheduling	45,7	Lacks opportunities to engage in face-to-face discussions	13,6
	Integrates multimedia tools	51,2	Does not assess students' problem-solving abilities and decision-making accurately	8,4
	Provides immediate feedback	34,2		
Molecular Workbench	Visualizes and manipulates molecular structures	47,8	Does not include all possible experiments in molecular science	16,7
	Conduct virtual experiments	59,8	Requires guidance to use the platform.	4,5
	Is a free, open-source platform	90,1	Is not engaging for some students	6,0
	Can be used across various scientific disciplines	23,4		
	Is applied to different educational levels	32,8	Lacks simulation quality, especially for highly detailed molecular models	12,3
Simulab	Offers highly realistic simulations	43,9	Has limitations in replicating complex laboratory LE	28,4
	Provides an interactive environment	57,3	Requires a subscription for advanced simulations or additional content	13,8
	Is affordable for institutions	17,5		
	Has a user-friendly interface	29,3		

Source: author's development.

The findings on the advantages and challenges of virtual laboratories/platforms can be used to develop organizational and pedagogical recommendations to introduce IVLs for distance learning in natural sciences.

Discussion

The literature review demonstrated that IVLs are an extensive topic within the scientific discourse and includes the definition of the virtual laboratory concept (Hassan et al., 2022) and explains its functions in LE (Kok et al., 2021; Reginald, 2023). Special attention was paid towards the characteristics of IVLs, including the possibility to simulate a real-life laboratory environment (Kikari et al., 2024), formation of conceptual understanding through digital tools and visualization (Zhang & Liu, 2023). Other findings stress that virtual laboratories are usually interactive platforms encouraging students to actively participate in educational exercises (Banda & Nzabahimana, 2022). Specific findings demonstrate that IVLs offer personalization and immediate feedback (El Kharki et al., 2021; Li & Liang, 2024), and they incorporate multimedia resources to enhance the efficiency of the educational process (Qawaqneh et al., 2023). Studying the characteristics of IVLs in digital learning in natural sciences, it was found that they include interactivity, visualization, adaptive learning, incorporation of real-time data and analysis tools, virtual simulations, and real-life laboratory exercises. Besides, they can perform complex procedures virtually. Special attention was paid to the analysis of IVLs in distance learning regarding natural sciences subjects (physics, chemistry, biology, earth science, engineering, environmental science, healthcare, and medicine).

However, while these characteristics demonstrate considerable promise, the literature also reveals important gaps and inconsistencies in how IVLs are defined and evaluated across studies, suggesting a lack of consensus that may hinder their systematic adoption. Special attention in scientific literature and methodical documents was paid to the criteria of efficiency of IVLs. They name interactivity (Sapriati et al., 2023), accessibility (Raman et al., 2022), and cost-effectiveness (Ron-Valenzuela et al., 2022) as the main requirements for IVLs used in the context of distance learning. Yet, these sources often lack a systematic and comprehensive analysis of efficiency criteria specifically tailored for natural sciences distance learning, which points to an important research gap. The descriptive research revealed that such laboratories should meet the following criteria to be effective within LE: accessibility, modeling, interactivity, adaptability to users, accuracy, cost-effectiveness, assessment and feedback, and alignment with curriculum. These criteria contribute to developing a compelling interactive virtual laboratory in the context of distance learning that makes teaching natural sciences subjects a motivating, engaging, and professionally oriented process.

Despite the positive impact of IVLs on teaching natural sciences in distance mode, their usage may bring certain challenges. For example, Zhao et al. (2023) indicated that these laboratories cannot replace the manual skills applied in the traditional laboratory setting. Some IVLs require high-performance hardware and specially designated software that does not make them accessible to all higher education institutions (Sellberg et al., 2024). High-quality IVLs, especially with 3D simulations, VR, or AR integration, can be expensive for some institutions (Klami et al., 2024; Vahdatikhaki et al., 2023; Zhao et al., 2023). As a result, open-access platforms are integrated but do not provide full content or have limitations in replicating complex laboratory LE. Many virtual laboratories are not flexible and use preliminary developed educational content (Södervik et al., 2021). In addition, some findings demonstrate that IVLs have difficulties in student engagement and assessment (Sapriati et al., 2023; Shamshin, 2021). Higher education institutions must balance these challenges to integrate IVLs effectively into the educational process. To address this, organizational and pedagogical recommendations should be designed.

The organizational recommendations for developing IVLs for distance learning in natural sciences focus on creating a structured and adaptable framework that integrates technology with curriculum objectives. They deal with selecting high-quality virtual laboratory platforms, collaborating with technology experts to ensure that the laboratory functions accurately, and advanced training for instructors. In this context, the pedagogical recommendations refer to the creation of adjustable educational content and the implementation of appropriate didactic models to maximize the potential of IVLs in distance learning. Importantly, these recommendations were validated through expert reviews to confirm their relevance and effectiveness. This introduces their practical application and supports their role in enhancing teaching and learning outcomes in distance education.

Higher education institutions can apply the findings to improve their curriculum and enhance the efficiency of the educational process. Implementing IVLs may improve distance learning and make teaching natural sciences subjects more interactive, accessible, and engaging for students. Furthermore, the research outcomes can help create an uninterrupted educational process in times of crisis. The examination implications highlight the need to elaborate educational guidelines that support the adoption of innovative digital tools, which are important for the development of students' professional competencies in increasingly digital scientific fields.

Conclusions

The research proves that IVLs have become an integral technology in distance learning of natural sciences. They enable the creation of immersive, real-life simulated environments where students can effectively visualize theoretical concepts and develop experimentation skills. Notably, the study highlights that the effectiveness of a virtual laboratory hinges primarily on its interactivity, which drives student engagement and fosters a collaborative atmosphere in remote settings. Additional key criteria include accessibility and adaptability, which together enhance the overall capabilities of IVLs within distance education contexts.

Six virtual laboratory platforms were selected based on an analysis of scientific sources and methodical documents (PhET, Labster, VLabs, eScience Labs, Molecular Workbench, and Simulab). During the investigation, their characteristics were revealed. Similar characteristics include distance learning in natural sciences, conducting practical interactive experiments and visualization of complex scientific concepts, interactivity, incorporating gamified elements, and integrating with LMS. To support the effective development of IVLs for natural sciences distance education, targeted organizational and pedagogical recommendations were formulated.

At the same time, the research possesses some limitations. They refer to the reliance on secondary data sources such as methodological documents or institutional guidelines. They may not fully explain the latest technological advancements since they frequently change, considering several internal and external factors. The study may also be limited due to a lack of empirical data. This may create difficulties in evaluating the practical challenges of using IVLs in distance learning and designing pedagogical recommendations for higher education institutions.

Future research should focus on conducting empirical experiments to determine the impact of IVLs on students' knowledge quality. Also, in the future, it is essential to investigate the peculiarities of implementing VR/AR applications in IVLs to enhance the efficiency of distance learning in natural sciences.

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