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PEDAGOGICAL FOUNDATIONS OF USING VIRTUAL LABORATORIES IN BIOLOGY EDUCATION TO SUPPORT SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

This study explores the pedagogical integration of virtual laboratories in biology education. It adopts a theoretical and analytical approach, reviewing pedagogical frameworks and synthesizing recent empirical findings. The results show that virtual laboratories enhance student motivation, scientific literacy, critical thinking, and digital competence. These benefits emerge because simulations provide flexible and safe environments that allow repeated experimentation without material constraints, making abstract biological processes more accessible. Additionally, virtual laboratories support inclusive and differentiated instruction, especially in settings with limited access to physical labs. Despite their potential, challenges remain in terms of teacher readiness, infrastructure, and curriculum alignment. Addressing these issues through professional development and institutional support can maximize the effectiveness of virtual laboratories. The findings suggest that when grounded in sound pedagogy, virtual laboratories complement traditional laboratory practices and contribute to a more equitable and future-oriented biology education. This study supports sustainable development goals (SDGs).

Keywords: Biology education, Digital technologies, Inquiry-based learning, Pedagogy, Virtual laboratory.

1. Introduction

The rapid digitalization of education has significantly transformed how teaching and learning are designed and implemented across all levels [1]. In science education, particularly biology, laboratory practice plays an essential role in developing students' experimental skills, scientific reasoning, and research competencies. However, several barriers hinder the optimal implementation of traditional laboratory activities, such as limited access to physical infrastructure, safety concerns, high operational costs, and disparities between urban and rural educational institutions. These challenges often restrict equal learning opportunities, especially in resource-constrained environments.

Table 1 presents a summary of previous studies examining the effectiveness of virtual laboratories in science education. These studies reveal that scenario-based simulations, inquiry-based learning, and hybrid approaches combining virtual and physical labs all contribute to improved student outcomes. The body of evidence continues to grow, especially following the post-pandemic shift to digital learning environments, highlighting both the potential and limitations of virtual labs.

Virtual laboratories simulate real-world experiments through interactive digital platforms, allowing students to engage in scientific investigations within safe, cost-effective, and repeatable environments [2-6]. These tools align closely with constructivist and inquiry-based paradigms, emphasizing active participation, exploration, collaboration, and learner autonomy. When integrated into blended or online models, they also support differentiated instruction and promote inclusivity, particularly in low-resource settings. Furthermore, virtual labs foster 21st-century skills such as critical thinking, digital literacy, and scientific communication, making them highly relevant in modern biology education.

Table 1. Previous research.

No.	Title	Ref.
1	The effectiveness of scenario-based virtual laboratory simulations to improve learning outcomes and scientific report writing skills	[7]
2	Enhancing Students' Scientific Literacy Using Virtual Lab Activity with Inquiry-Based Learning	[8]
3	Are virtual physiology laboratories effective for student learning?	[9]
4	Effect of virtual laboratory combined with demonstration on scientific literacy in lower-secondary students	[10]
5	Reviews on wet-lab e-learning post-COVID and learning analytics in virtual labs	[11]
6	Adding immersive virtual reality to a science lab simulation causes more presence but less learning	[12]
7	Virtual and remote labs in education: A bibliometric analysis	[13]

Despite their benefits, the successful integration of virtual laboratories into biology curricula requires clear pedagogical design and instructional alignment. Challenges remain, particularly in teacher readiness, infrastructure availability, and curriculum mapping. Therefore, this study aims to investigate the pedagogical foundations of virtual laboratory implementation, identify critical success factors, and assess their effectiveness in fostering engagement and science competencies. The novelty of this paper lies in combining pedagogical theory with empirical evidence to provide comprehensive guidance for the meaningful use of virtual laboratories in biology education. This study supports Sustainable Development Goals (SDGs).

2. Literature Review

Biology education traditionally places significant emphasis on laboratory activities, as these are vital for helping students develop scientific inquiry skills, observe phenomena, and apply theoretical concepts to practical situations. Many reports regarding biology education have been well-documented [14-16]. However, many educational institutions, especially in developing regions, face systemic challenges such as insufficient laboratory space, a lack of equipment, and safety concerns. These constraints have often resulted in limited access to hands-on experimental experiences, leading to gaps in students' scientific understanding and competencies.

To address these limitations, educational researchers and institutions have explored the integration of virtual laboratories as a complementary or alternative tool. Several studies have confirmed their potential. For instance, scenario-based simulations have been shown to enhance students' understanding of biological processes and improve their scientific report writing skills. Similarly, inquiry-based virtual labs promote deeper engagement with content and foster scientific literacy through structured investigation and data analysis.

In addition, studies comparing traditional and virtual laboratory formats, especially in physiology and life science education, suggest that virtual laboratories can produce equivalent or even superior learning outcomes in certain contexts. The advantage lies in their ability to simulate complex or hazardous experiments that might be otherwise inaccessible due to logistical or ethical constraints. Furthermore, combining virtual simulations with physical demonstrations has shown positive effects on students' conceptual understanding and ability to transfer knowledge across related topics.

Thus, in the context of biology, virtual laboratories address a dual need: (i) overcoming the limitations of physical labs, and (ii) providing interactive and scalable platforms for scientific exploration. These tools are especially valuable for topics that require detailed visualization, such as molecular biology, cellular processes, ecology, and genetic simulations.

From a pedagogical standpoint, the integration of virtual laboratories is strongly supported by constructivist and inquiry-based learning theories. These approaches emphasize active engagement, knowledge construction through experience, and the importance of context in shaping understanding. Virtual labs support these principles by enabling students to explore scientific concepts through experimentation, hypothesis testing, and iterative feedback.

Pedagogically, virtual labs serve multiple functions: they enhance learner autonomy, foster motivation, and provide adaptive learning environments. They also support differentiated instruction by allowing students to proceed at their own pace and revisit procedures multiple times. Such features are particularly beneficial in mixed-ability classrooms and inclusive education settings. Moreover, the shift toward digital and blended learning models following the COVID-19 pandemic has accelerated the adoption of technology [17-22].

Research emphasizes their role in fostering 21st-century skills such as critical thinking, collaboration, and digital competence, which are essential for both academic success and workforce readiness [23-28]. However, effective implementation depends not only on the technology itself but also on the pedagogical readiness of instructors. Studies highlight the need for professional development, clear instructional strategies, and alignment with curriculum standards to maximize educational outcomes.

In summary, while virtual laboratories offer clear pedagogical benefits, their effectiveness hinges on thoughtful integration into instructional design. The existing literature underscores the importance of teacher facilitation, appropriate scaffolding, and alignment with learning objectives to ensure that virtual labs do more than replicate traditional experiments; they must transform how students learn and engage with science.

3. Method

This study employed a theoretical and analytical research design to explore the pedagogical foundations of virtual laboratories in biology education. The approach involved a comprehensive review and synthesis of both theoretical frameworks and empirical studies related to the use of digital laboratories in science learning. The objective was to identify the pedagogical principles, implementation challenges, and educational outcomes associated with virtual laboratories in diverse instructional settings. The methodological framework was structured around three core components:

(i) Review of pedagogical theories, particularly constructivist and inquiry-based learning models that support the use of simulations and interactive technologies in science education.

(ii) Analysis of didactic principles, including scaffolding, differentiation, and student-centered instruction, as applied to digital laboratory environments.

(iii) Evaluation of empirical evidence drawn from recent peer-reviewed research to assess the effectiveness of virtual laboratories in enhancing learning outcomes and competencies in biology.

The literature review focused on publications from 2020 to 2024, selected through databases such as Scopus, Web of Science, ERIC, and Google Scholar. The inclusion criteria required that each study:

(i) Address the use of virtual laboratories in biology or related science education fields.

(ii) Include a discussion of pedagogical or didactic dimensions.

(iii) Provide empirical data on student learning outcomes, competencies, or instructional implementation.

Both experimental and review-based studies were included to ensure a balanced and comprehensive understanding of the topic. The comparative analysis examined educational settings such as secondary education, higher education, and online learning environments, identifying shared patterns, context-specific differences, and pedagogical implications.

Special attention was paid to studies focusing on the development of critical thinking, scientific literacy, digital competence, and other 21st-century skills. The results were categorized thematically to allow for structured interpretation in the next section. This methodological approach ensured that findings were grounded in both theoretical relevance and practical applicability, forming the basis for the analysis presented in the Results and Discussion chapter.

4. Results and Discussion

4.1. Pedagogical benefits

Table 2 presents the key pedagogical benefits of integrating virtual laboratories in biology education, as identified in recent studies. The evidence supports that virtual laboratories significantly contribute to enhancing student engagement, improving scientific literacy, fostering critical thinking, encouraging collaboration, and developing digital competence.

Table 2. Pedagogical benefits of virtual laboratories.

Pedagogical Dimension	Key Outcomes	Evidence from Studies
Engagement & Motivation	Increased student interest and participation in lab activities	[7-9]
Scientific Literacy	Improved ability to analyze, interpret, and report data	[8, 10]
Critical Thinking	Enhanced problem-solving and inquiry-based reasoning	[8, 9]
Collaboration & Inclusivity	Support for group work and accessibility in low-resource contexts	[11, 13]
Digital Competence	Strengthened technological and scientific skills	[8, 12]

First, several studies indicate that virtual laboratories increase student motivation and participation by providing an interactive and visually engaging learning environment. This aligns with findings from scenario-based simulations and inquiry-based platforms, which report heightened curiosity and learner autonomy. These simulations allow learners to perform experiments multiple times, reinforcing understanding without the constraints of physical resources or safety risks.

Second, scientific literacy is notably enhanced, as virtual laboratories guide students through structured investigation processes, including data collection, analysis, and interpretation. These experiences support the development of essential academic competencies such as observation, hypothesizing, and drawing evidence-based conclusions.

Third, virtual laboratories promote critical thinking by encouraging students to apply concepts, test hypotheses, and reflect on outcomes within simulated environments. These processes mirror authentic scientific inquiry and align with constructivist models that prioritize problem-solving and reasoning skills.

Additionally, virtual laboratories enable collaborative and inclusive learning. Students can work in pairs or groups through digital platforms, sharing roles and discussing results, which promotes peer interaction. Moreover, the accessibility of virtual labs makes them a valuable resource for schools lacking advanced laboratory infrastructure, thereby supporting educational equity.

Finally, digital competence emerges as a cross-cutting benefit. Engaging with virtual tools enhances students' familiarity with scientific software, interfaces, and online experiment protocols, equipping them with the skills necessary for future STEM pathways.

4.2. Implementation challenges

Table 3 outlines the major challenges identified in the implementation of virtual laboratories within biology education. While the pedagogical benefits are well-documented, several structural and instructional issues continue to hinder their full integration into educational systems.

Table 3. Challenges in implementing virtual laboratories.

Challenge	Source	Implications
Teacher readiness & methodological skills	[8, 10, 12]	Need for professional development and pedagogical training
Cost and technological infrastructure	[9, 12]	High investment required for immersive or advanced platforms
Curriculum integration	[11, 13]	Requires alignment with national education standards and assessments
Learning effectiveness vs. immersion	[12]	VR increases presence but may reduce conceptual outcomes
Long-term impact assessment	[11, 13]	Limited evidence on sustained learning gains

One of the most recurring challenges is teacher readiness and methodological competence. Many educators are not sufficiently trained in designing or facilitating virtual experiments, particularly in aligning digital activities with learning objectives and assessment strategies. This gap often leads to superficial integration, where virtual labs are used as isolated tools rather than as part of coherent instructional design.

Another concern involves the cost and technological infrastructure required to support advanced simulations or immersive environments such as VR-based laboratories. Although basic virtual labs are relatively accessible, high-fidelity systems demand robust hardware, software, and reliable internet connectivity—conditions not always available in under-resourced schools.

Curriculum integration presents an additional challenge. Incorporating virtual labs into existing syllabi requires curricular alignment, modification of assessment formats, and policy-level support. In systems where national education standards are rigid, this integration can be slow or inconsistently applied.

Moreover, there is growing awareness that immersive learning environments, such as those using virtual reality, may sometimes prioritize sensory engagement over cognitive processing. While VR increases a sense of presence, it can distract from conceptual understanding if not carefully guided.

Finally, there is a notable lack of longitudinal studies assessing the sustained impact of virtual laboratories on student learning. Most research focuses on short-term outcomes, leaving questions about the long-term development of competencies unanswered.

4.3. Interpretation of findings (discussion)

The findings from previous sections reveal that virtual laboratories offer significant pedagogical value in biology education, particularly in enhancing student engagement, conceptual understanding, and the acquisition of essential 21st-century skills. These results are consistent with global trends in educational innovation, where technology-supported learning environments are increasingly emphasized for their potential to personalize instruction and promote active learning.

The benefits observed (such as increased motivation, improved scientific literacy, and enhanced digital competence) align closely with the constructivist and inquiry-based pedagogies underpinning science education reform. Students interacting with virtual labs are not only replicating experimental procedures but also developing skills in analysis, reflection, and evidence-based reasoning. These competencies are foundational for scientific literacy and are critical in preparing learners for future academic or professional paths in STEM fields.

However, the challenges identified in implementation serve as a cautionary note. The success of virtual laboratories depends not merely on the availability of software or hardware, but on thoughtful instructional design and the capacity of educators to integrate these tools into broader curricular goals. Teachers' limited methodological preparedness can dilute the pedagogical potential of virtual labs if activities are used in isolation or without alignment to learning outcomes. Therefore, virtual laboratories should not be seen as replacements for traditional laboratories, but rather as complementary tools that extend learning opportunities, especially in settings where access to physical resources is constrained.

The issue of immersion versus learning, particularly in the context of virtual reality (VR), presents an important nuance. While high levels of sensory engagement can increase student interest, they may also introduce cognitive overload or distraction if instructional scaffolding is not properly embedded. This highlights the importance of designing virtual lab experiences with clear learning objectives and structured guidance to maintain cognitive focus and ensure knowledge retention.

Moreover, the current evidence base is largely centered on short-term outcomes. There remains a pressing need for longitudinal research that examines how sustained exposure to virtual laboratories influences students' scientific thinking, practical competencies, and academic progression over time. Addressing this research gap is vital for informing policy decisions and justifying large-scale investments in educational technology.

In sum, while virtual laboratories clearly support the modernization of biology education, their full potential will only be realized when they are implemented as part of an intentional, pedagogically sound instructional framework that includes professional development for educators, curriculum alignment, and equity of access.

4.4. Policy, practice, and SDG implications

The integration of virtual laboratories into biology education has several implications for educational policy formulation, teaching practice, and alignment with the SDGs. These implications extend beyond classroom-level implementation and call for systemic strategies to support digital transformation in science education.

From a policy perspective, the widespread adoption of virtual laboratories requires sustained investments in digital infrastructure, teacher training programs, and the development of national curriculum frameworks that accommodate virtual experimentation. Ministries of education and related authorities should develop guidelines that clearly define learning outcomes, assessment methods, and standards for the use of virtual laboratories. Without such top-down support, adoption efforts may remain fragmented and inequitable across different regions or institutions.

In terms of teaching practice, professional development plays a central role. Teachers need targeted training not only in the technical operation of virtual lab platforms but also in the pedagogical strategies for their effective use. This includes designing inquiry-based learning activities, scaffolding student engagement, and integrating virtual labs into lesson plans that promote critical thinking and data interpretation. Equipping educators with these skills can help bridge the gap between technological potential and actual learning outcomes. These changes also align strongly with the SDGs, particularly:

(i) SDG 4: Quality Education. Virtual laboratories promote equitable and inclusive education by providing access to high-quality experimental learning for all students, regardless of geographic or economic barriers. They enable differentiated instruction, support diverse learning needs, and facilitate the development of scientific competencies essential for lifelong learning.

(ii) SDG 9: Industry, Innovation, and Infrastructure. The development and integration of virtual laboratories reflect innovation in educational technology. They require and stimulate investments in ICT infrastructure, encourage the local development of educational software, and contribute to the modernization of instructional systems in line with global digital advancements.

Moreover, the intersection of virtual laboratories with these SDGs underscores their relevance not only as teaching tools but also as drivers of systemic educational reform. In contexts where physical laboratory spaces are scarce or outdated, virtual laboratories offer scalable, sustainable alternatives that can bridge infrastructure gaps without compromising the quality of learning. This study adds new information regarding SDGs, as reported elsewhere (Table 4).

To fully harness this potential, policies must emphasize equity of access, particularly in rural and underserved areas. Providing open-source or low-cost virtual lab platforms, combined with reliable internet access and device availability, will ensure that the benefits of this innovation are shared broadly. The pedagogical, infrastructural, and policy implications of virtual laboratories make them highly compatible with global development agendas. Their thoughtful implementation can help modernize education systems, democratize access to science education, and support broader national and international goals for sustainable, inclusive innovation.

Table 4. Previous studies on SDGs.

No.	Title	Ref.
1	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	[29]
2	Sustainable packaging: Bioplastics as a low-carbon future step for the SDGs	[30]
3	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting SDGs	[31]
4	HIRADC for workplace safety in manufacturing: A risk-control framework and bibliometric review to support SDGs	[32]
5	Techno-economic analysis of production ecobrick from plastic waste to support SDGs	[33]
6	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia’s green tourism policy and the SDGs	[34]
7	Definition and role of sustainable materials in reaching global SDGs completed with bibliometric analysis	[35]
8	Bibliometric insight into materials research trends and innovation to support SDGs	[36]
9	Physical adaptation of college students in high-altitude training to support SDGs	[37]
10	Enhancing job satisfaction through HRIS and communication: A commitment-based approach to SDGs	[38]
11	Enhancing innovative thinking through theory-based instructional model to support SDGs	[39]
12	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving SDGs	[40]
13	Enhancing occupational identity and self-efficacy through self-education in art/design aligned with SDGs	[41]
14	Integrating generative AI-based multimodal learning in education to enhance literacy aligned with SDGs	[42]
15	Dataset on Sulawesi schools and cultural implications to support SDGs	[43]
16	Enhancing professional readiness in vocational education aligned with SDGs	[44]
17	School feeding program and SDGs in education: Linking food security to learning outcomes	[45]
18	Influence of eco-friendly packaging on consumer interest to meet SDGs	[46]
19	SDG 12 implementation through lemon commodities and waste reduction	[47]
20	Mediterranean diet patterns and sustainability to support SDGs	[48]
21	Education on food diversification through infographic to improve SDGs	[49]
22	Safe food treatment technology to achieve SDG zero hunger and optimal health	[50]

5. Conclusions

This study highlights the pedagogical value of integrating virtual laboratories into biology education. When aligned with inquiry-based and constructivist principles, virtual labs enhance student motivation, critical thinking, scientific literacy, and digital competence. They provide accessible and flexible environments for experimentation, especially in contexts with limited physical resources, making them valuable complements to traditional laboratory practices. However, the effective use of virtual laboratories depends on teacher readiness, adequate infrastructure, and curriculum integration. Without these, their benefits may not be fully realized. Teachers must be equipped with both technical skills and pedagogical strategies to design meaningful virtual lab experiences.

Institutions should support this integration through investments in training and technology, as well as policy frameworks that promote equitable access. To maximize their impact, it is recommended that virtual laboratories be formally incorporated into science curricula. This includes aligning them with learning objectives, ensuring inclusivity, and providing continuous professional development. Further research is needed to examine long-term effects on learning and skill development. Virtual laboratories represent a practical and innovative response to evolving educational needs. Their thoughtful application can improve the quality and inclusiveness of biology education while supporting global goals such as SDG 4 and SDG 9.

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