VHEalthLab

Creation of Open-Access Virtual laboratories (VL) for teaching in STEM education: Biology across the Health Sciences

WP5 Task 5.2

TRANSNATIONAL REPORT

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Current practices in using VLs in STEM and health education have shown significant advancement and effectiveness, particularly highlighted by the articles

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Executive Summary

This transnational report examines the current use of virtual laboratories (VLs) in STEM and health education across four European countries: Cyprus, Greece, Spain and Romania. It forms part of a broader European initiative aimed at strengthening digital capacity and inclusive teaching practices in experimental science education.

Virtual laboratories offer an effective means of supporting science education through scalable, interactive environments that complement or replace traditional laboratories. Their relevance to this project lies in their capacity to enhance conceptual understanding, encourage inquiry-based learning and promote accessibility in diverse educational settings.

The findings highlight varying levels of implementation across the partner countries. Greece demonstrates mature integration at the university level; Spain applies large-scale platforms in secondary education with potential for expansion; Romania focuses on inclusive applications, particularly for learners with special educational needs; and Cyprus is at an early stage, with growing institutional engagement.

Common challenges include limited infrastructure, gaps in teacher training and a lack of standardised frameworks for curriculum integration and evaluation. Addressing these issues is essential to ensure the sustainable and effective use of VLs.

The report concludes that virtual laboratories are a valuable component of modern science education. Their wider adoption would benefit from coordinated strategies and policy support across European education systems.

1. Introduction

1.1. Context of the European project and its focus on STEM and Health education.

In recent years, the demand for STEM education has grown due to its role in developing essential 21st-century skills such as critical thinking, problem-solving, and digital literacy. However, there has been a decline in student interest in STEM fields across Europe, raising concerns about the future workforce. Additionally, science education faces the challenge of ensuring that students acquire hands-on laboratory skills in contexts where physical lab access is limited. Virtual Laboratories (VLs) have emerged as an innovative solution, providing realistic experimental environments that allow students to develop practical competencies remotely, complementing face-to-face lab work and enhancing engagement in STEM and health-related disciplines.

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The VHEalthLab project responds to this challenge through an open-access e-learning platform focused on STEM and Health Science education. It hosts virtual biology laboratories designed to support higher-education students in acquiring lab-based skills through interactive, inquiry-based learning (IBL) - emphasising questioning, use of evidence, and reflection - with adaptations suitable for secondary education. Available in four EU languages (English, Greek, Spanish, Romanian), the resources can be used remotely, as classroom supplements, or integrated into blended formats. Inclusivity is a cross-cutting principle: the platform, pedagogical guidelines, and training modules provide practical strategies to address gender gaps in STEM participation and diverse learning needs. By embedding VL practice within STEM and health curricula, VHEalthLab promotes accessible, high-quality training that strengthens students' scientific competencies and prepares them for professional pathways.

1.2. Objectives of the report

The primary objective of this report is to identify the current use of Virtual Laboratories (VLs) in higher education across the partner countries and other EU nations, with a specific focus on STEM and Health Science education. By examining how VLs are integrated into university-level teaching; regarding practices, methodologies, and challenges that characterise their uptake, the report establishes an evidence base for improving integration and optimising pedagogical impact across different educational contexts.

The report forms a core deliverable within Work Package 5 (WP5), advancing the project's Priority Objectives (POs) 5 and 6. It directly informs the development of pedagogical guidelines for effective VL implementation in fully online, blended, and classroom-supplementary scenarios. These guidelines are packaged as an open-access online course with supporting materials and treat inclusion as a horizontal priority, offering practical recommendations for learners with special educational needs, non-native speakers, and for addressing the gender gap in STEM.

In scope, the report (i) synthesises the European literature on VL adoption in STEM and Health Science Education, (ii) details the methodology used for implementation studies in the partner countries, and (iii) presents overall results from the evaluation of the Pedagogical Guidelines, Training Module 1, and four open-access VHEalthLab virtual labs: Laboratory Safety; Light Microscopy; Cell Structure and Function; Cell Division). It concludes with evidence-based recommendations for policy and practice.

Finally, the report is intended for policymakers and higher-education stakeholders. It provides actionable, evidence-based guidance to support wider adoption of VLs, strengthen digital-education strategies, reduce accessibility barriers, and improve

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student engagement and learning outcomes in STEM at the secondary and university level.

2. Methodology

2.1. Methodological approach for the literature review

To gain a comprehensive understanding of the current use of VLs in STEM, Biology and Health education at the university level across the partner countries (Cyprus, Greece, Spain and Romania), a systematic literature review was conducted. This review aimed to identify existing research, best practices, and challenges associated with VL implementation, providing a solid foundation for the development of pedagogical guidelines and training modules. The literature search was performed at a National and European level, ensuring a broad perspective on VL usage in different educational contexts.

The other selected EU countries were Finland, Estonia, Bulgaria, Germany, France, Portugal, The Netherlands and Italy, according to a selection criteria based on the disparities in VL adoption across European Countries.

2.2. *Rationale for the selection of the EU countries*

The rationale for conducting a systematic literature review (SLR) on virtual labs in biology programs across Europe focuses on understanding their diverse applications and impacts in higher education. Virtual labs have gained significance, particularly during the COVID-19 pandemic, which accelerated the transition from traditional to virtual environments (Roda-Segarra, 2021; Rahman et al., 2022).

2.2.1. *Current Landscape*

The brief literature reveals a fragmented landscape of VL platforms, predominantly used in medical and biology fields education across Europe (Elmoazen et al., 2023). While studies indicate that virtual labs enhance self-regulated learning and bridge theoretical knowledge with practical experience, their impact on student independence and motivation remains underexplored (Sapriati et al., 2023; Zhang et al., 2021). Evidence suggests improvements in understanding abstract concepts and laboratory skills, yet challenges persist in developing effective learning media (Azizah & Aloysius, 2021; Udin et al., 2020).

2.2.2. *Disparities in VL Usage in HE Across European Countries*

Disparities in usage stem from factors like technological infrastructure, educational policies, and investment levels. Countries such as Spain and Germany are leaders in research and development of virtual labs due to their robust digital infrastructure

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(Raman et al., 2022). Initiatives like the NEWTON project under the EU's Horizon 2020 program aim to standardize usage across Europe, particularly for STEM education (Lynch & Ghergulescu, 2017). However, regions with limited internet access face significant barriers to effective implementation (Rafieemehr et al., 2024).

2.2.3. *Categorization of Countries*

Disparities in Virtual Lab adoption across European countries:

Advanced Countries

- Spain: Leading in research and integration of virtual labs.
- Germany: Strong framework with high research output.
- Netherlands: Innovative educational practices support extensive use.
- Finland: Effective integration within biology programs.
- France: Significant progress in adopting virtual labs.

Medium Countries

- Austria: Moderate engagement with emerging initiatives.
- Portugal: Several universities involved but less impactful than leaders.
- Slovakia: Progressing but still behind established nations.
- Greece: Moderate involvement with collaborative projects.
- Italy: Developing infrastructure with several participating universities.

Less Advanced Countries

- Romania: Limited infrastructure and minimal integration into higher education.
- Bulgaria: Minimal engagement indicates a need for development.
- Lithuania: Developing usage with few active research efforts.
- Estonia: Struggling to fully integrate virtual labs despite advancements in digital education.

2.2.4. *Rationale for the selection*

Selecting countries for a systematic literature review should consider:

- **Diversity in Research Output**: A range from high to low output provides insights into utilization across Europe.
- **Educational Integration**: Varying levels reveal best practices and challenges faced by different nations.
- **Infrastructure Differences**: Examining different digital infrastructures highlights opportunities and barriers.

This categorization enables partners to select countries that align with their interests, offering insights into the use of virtual labs across diverse educational contexts in the EU. The references highlight both innovations and disparities in adoption in biology education across Europe.

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Table 1. List of countries reviewed by partners.

Country*	Partner Organization
Cyprus	UNIC/ MOEC
Greece	AUTH
Spain	USC
Romania	ASCENDIA
Finland (Advanced)	Cyprus (UNIC/MOEC)
Estonia (Less Advanced)	Cyprus (UNIC/MOEC)
Bulgaria (Less Advanced)	Greece (AUTH)
Germany (Advanced)	Greece (AUTH)
France (Advanced)	Romania (ASCENDIA)
Portugal (Medium)	Romania (ASCENDIA)
The Netherlands) (Advanced)	Spain (USC)
Italy (Medium)	Spain (USC)

*National country + 2 EU countries: one with advanced VR lab adoption, one with medium and/or and one with less VR lab adoption

2.3. Data analysis

The review process was conducted in two stages. The first stage involved selecting the appropriate databases for the literature search, defining the search strategy, and establishing the inclusion and exclusion criteria for the retrieved articles. The second stage focused on data analysis, where a set of guiding questions was used to systematically evaluate and extract relevant information from the selected studies.

Step 1. The selected database was Web of Science (WoS), due to its extensive collection of high-quality and peer-reviewed research articles. To complement this, each partner conducted additional searches in national academic databases, allowing for the inclusion of studies that may not be indexed in WoS but are nonetheless relevant to local educational practices. The search strategy was designed to maintain consistency across all participating countries, ensuring the comparability of findings.

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The keywords used in the search were: *“Virtual Lab” AND “Health Education” AND [Name of the country], “Virtual Lab” AND “STEM Education” AND [Name of the country]*, and *“Virtual Labs” AND “Biology Education” AND [Name of the country]*. The selection criteria were restricted to peer-reviewed journal articles (excluding book chapters and conference proceedings) published within the last five years (search period: 2020–2024), ensuring the inclusion of recent and high-quality research.

The first inclusion criterion focused on selecting empirical studies in which virtual laboratories had been implemented. This was determined through an initial screening by reading abstracts. The second inclusion criterion required selecting articles that specifically assessed the impact of virtual laboratories on students. These criteria ensured that the review focused on studies that provided empirical evidence of VL applications and their effectiveness in educational settings.

Step 2. The analysis of the previously selected articles was conducted by addressing the following key aspects:

- **Type of activities implemented in the virtual laboratory**: Activities were classified as open or closed, active or passive, contextualized or non-contextualized, and conducted individually or in groups.
- **Methodologies used**: The review examined whether the methodologies fostered interactivity or were non-interactive.
- **Impact on the learning process**: The studies were assessed to determine whether the virtual laboratory had a positive or negative effect on student learning.
- **Inclusion aspects**: Consideration was given to whether the studies addressed issues such as gender representation, educational difficulties, or other inclusion-related factors.
- **Identified challenges and needs**: Any difficulties or requirements for successful VL implementation were documented.
- **Educational implications**: The broader educational relevance of the findings was analysed.

By following this structured approach, the review aimed to gather the necessary information to complete the relevant sections of this report. The goal was to obtain a comprehensive overview of current university-level practices regarding the use of virtual laboratories in partner countries, as well as a broader perspective on VL adoption across other European countries. While the analysis of partner countries was conducted in greater detail, the findings from other countries were presented in a more concise format and summarized in a table, which consolidates the main features of the selected studies.

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To ensure clarity and proportionality in the presentation of findings, a dual approach was adopted based on the number of eligible studies per country. For countries with ten or fewer empirical studies meeting the inclusion criteria, the findings were synthesized qualitatively through narrative descriptions. Conversely, in cases where more than ten studies were identified, a quantitative summary was employed, using predefined analytical categories (e.g., type of activity, interactivity, impact on learning, inclusion aspects, and implementation challenges). This decision was taken to facilitate comparative analysis and to avoid extensive narrative repetition, allowing for a coherent and manageable presentation of results across highly heterogeneous national contexts.

2.4. Brief information about limitations in the scope of the analysis

Despite following a systematic methodology to review the literature on VLs in STEM and Health education, several limitations were encountered that affected the scope of the analysis.

One key limitation was the scarcity of empirical studies directly related to the use of VLs in higher education. While the initial searches in the different countries identified a large number of articles, a significant portion of these focused on virtual reality, gamification, or other digital learning tools rather than VLs specifically. As a result, only a limited number of studies met the inclusion criteria, particularly those that assessed the implementation of VLs in university settings and their impact on student learning. This constraint was observed across all partner countries, highlighting a general gap in research on VLs in higher education.

Additionally, the availability of country-specific data varied considerably, with some countries having more documented research on VL implementation than others. This led to disparities in the depth of analysis for different national contexts. While the review aimed to provide a comparative perspective, the findings from some countries were more detailed than others due to the limited number of relevant studies. Moreover, the inclusion criteria restricted the selection to peer-reviewed empirical studies published within the last five years (2020-2024), which may have excluded relevant insights from earlier foundational research on VLs.

Finally, the review primarily relied on English-language sources, which may have resulted in the omission of studies published in other languages that could provide additional context on VL practices in non-English-speaking regions. While efforts were made to consult national databases and relevant journals in each country, access to local studies was occasionally limited.

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These limitations should be considered when interpreting the findings of this report. Nevertheless, the review offers a valuable overview of existing VLs practices and highlights key gaps that can guide future research and policy development.

2.5. Methodological approach for VHEalthLab materials implementation

2.5.1. Data collection and research instruments

To generate robust evidence on the implementation of VHEalthLab, the project adopted a mixed-methods design, combining quantitative and qualitative data across the partner countries.The evaluation covered three components: Module 1: Introduction to Virtual Labs and Inquiry-Based Learning (IBL), the Pedagogical Guidelines, and four open-access virtual labs: Laboratory Safety, Light Microscopy, Cell Structure and Function, Cell Division. Participants were higher-education educators and pre-service teachers. While a common methodological core was maintained, implementation varied slightly across national contexts (e.g., timing, delivery mode, and language). These contextual particularities are documented in the country reports within the implementation report of the cross-country synthesis, available here.

Quantitative data

Pre-questionnaires and post-questionnaires

The evaluation employed a pre-post questionnaire design to gather structured feedback from participating educators. The pre-questionnaire was administered before participants were introduced to the VHEalthLab materials. It included Likert-scale items assessing digital readiness, familiarity with virtual labs, expectations regarding pedagogical outcomes, and a comment section.

After completing the training, a post-test questionnaire was administered. In addition to Likert-scale questions, the post-test questionnaire included a multiple-choice question about challenges encountered, several short-answer reflection questions about what they learned, how they perceived the materials, suggestions for improvements, and an open-ended feedback section. This dual approach allowed for numerical comparisons and a deeper understanding of the users' experience.

Qualitative data: *Interviews and Focus group*

The qualitative data were gathered through a series of written/oral interviews, as well as a focus group session, all structured around a predefined set of questions. Participants evaluated the VHEalthLab materials by reflecting on their navigation experience, overall perceptions, and instructional value; they also offered concrete suggestions for improvement and provided additional feedback on the platform and its resources.The questions were followed flexibly, adapting to the natural flow of the

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discussion. This combined approach ensured a comprehensive understanding of users' experiences and needs.

2.5.2. Methods for data analysis

Quantitative responses were examined descriptively to identify pre–post trends and stable patterns across contexts. The methods applied for the analysis of qualitative data are based on discourse analysis, specifically content analysis was used for the codification of written responses and oral interventions according to Braun and Clarke's six-step thematic framework, reducing 24 initial codes to five themes.

Ethical and quality considerations underpinned the process: participation was voluntary, informed consent was secured, and responses were anonymised. The staggered timing of national implementations, along with differences in language availability at the point of testing, introduces natural limitations on cross-country comparability, and sample sizes reflect the pragmatic realities of pilot implementation. Nevertheless, the mixed-methods approach, common instruments, and triangulation across sources provide a credible basis for transnational conclusions.

This transnational report presents the overall results derived from the methodology shared above. Full country implementation reports, detailing context, instruments, procedures, and disaggregated analyses, are included in the appendices and should be consulted for detailed evidence and interpretations [appendices].

3. Overview of findings from the literature review

This literature review identified 1,189 articles in total across 12 countries, with a focus on assessing the empirical evidence for VLs in higher education STEM and health fields. A key finding is the significant scarcity of empirical research in this domain, as only 50 studies ultimately met the criteria for full evaluation.

Germany stands out as the country with the highest number of relevant empirical studies, with 18 evaluated articles out of 207 empirical works. Greece also showed a significant body of research, with 11 evaluated studies out of 51 empirical findings. These figures suggest a relatively advanced state of VL implementation and systematic evaluation in these national contexts.

In contrast, several countries reported a limited number of eligible studies, despite a high initial volume of publications. For example, Spain identified 160 articles, but only 5 met the criteria for final analysis. Similarly, France (148 identified) and Italy (211) resulted in only 3 and 1 evaluated articles, respectively. These discrepancies indicate a high proportion of theoretical or non-assessable publications within those countries.
Furthermore, countries such as Estonia and Bulgaria revealed a notable absence of eligible studies, with Estonia reporting no empirical articles and Bulgaria none that fulfilled the final evaluation criteria. These cases highlight significant gaps in research

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and the need for further empirical exploration regarding VL use in these educational systems.

These findings are summarized in **Table 2**, which provides an overview of the number of articles found, their classification (theoretical or empirical), and the final number of evaluated studies per country.

Table 2. Summary of articles identified, classified, and evaluated per country.

Country	Number of articles identified	Theoretical	Empirical	Evaluated
Romania	22	8	14	2
Cyprus	7	4	3	3
Spain	160	3	5	5
Greece	82	31	51	11
Finland	15	10	5	4
Estonia	2	2	0	0
Bulgaria	17	7	10	0
Germany	289	82	207	18
France	148	61	87	3
Portugal	80	39	41	2
The Netherlands	156	2	2	1
Italy	211	3	5	1
Total	1189	252	430	50

4. Literature review findings from partner countries

In this section, the current practices in the use of VLs at university level in STEM and health education identified in the literature review are discussed. Methodologies used and the type of activities provided in VLs need to be briefly reported as well as the impact of VLs on students' learning, are briefly discussed and presented.

4.1. Cyprus

4.1.1. Current practices

In the search conducted through EPIC Database, UNIC Local Database of Digital Library and Google scholar database, a large number (over 100) of articles were identified using the keyword combination "Virtual Labs" AND "Biology Education" / "STEM Education" / "Health Education". However, most were not related to the topic of

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interest, or they were not related to Cyprus and excluded based on the exclusion criteria. Ultimately, 3 articles were selected that met the criteria and evaluated the application of virtual laboratories in the classroom.

Current practices related to virtual laboratories in the classroom are examined in one out of the three articles evaluated. In the article published by Papalazarou et al, in 2024, the analysis aims to investigate which of the two modes (virtual or physical) is the most effective for high-school students, in terms of conceptual understanding and attitudes. For the purpose of this article, four educational scenarios were created: two in the field of Mechanics and two in that of Electricity. Although the project is implemented at the pre-university level, its virtual laboratories could be adapted for university-level.

The other two articles do not present virtual laboratories in the traditional sense but instead they examined other aspects of the education prosses. The article published by Nisiforou et al in 2024 examines VR/AR integration readiness through a comprehensive e-readiness survey of 127 participants and the article published by Tsivitanidou et al in 2021 aimed at examining students' attitudinal profiles and, secondly, at exploring the potential differences of those profiles in relation to conceptual learning gains and perceptions of the learning experience

4.1.2. *Methodologies and type of activities*

In the article published by Papalazarou et al. in 2024, the educational scenarios used for the implementation of the courses were designed on the online platform Graasp and followed the inquiry-based learning approach. The experimental design was between participants. The same educational scenarios were used for both labs. One group (A) of students first engaged in the VL (Mechanics) and then in the PL (Electricity), while the other group (B) first engaged in the PL (Mechanics) and afterwards in the VL (Electricity). Apart from changing the lab mode, they followed the same procedure. The students were working in groups of 2–3. On the day of the final lesson, the students completed the attitude questionnaire, evaluating their experience with each subject and lab method. All questionnaires were filled in individually.

In the article published by Nisiforou et al in 2024 the methodology included a comprehensive e-readiness survey of 127 participants (98 faculty members and 29 HE leaders) across eight dimensions whereas the article published by Tsivitanidou included a clustering analysis among two attitudinal profiles: the low-attitudes profile and digital technologies-related attitudes.

4.1.3. *Educational Impact*

The first evaluated article titled "Assessing Institutional Readiness for Emerging Technologies Integration in Higher Education" that was published in the Journal of Interactive Learning Research argues that the main educational implications inclide the

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evolution of institutional governance structures must incorporate faculty representation in technology-related decision-making includes the formulation of standardized evaluation methods for VR/AR educational experiences. Strategic foresight, ongoing investment, and synergies between institutions, technology developers, and policymakers are crucial for establishing best practices and ensuring sustainable implementation while adhering to educational standards. The anticipated success of VR/AR integration fundamentally relies on institutional capability to develop adaptive policies that embrace technological advancements while ensuring pedagogical effectiveness and institutional sustainability.

The second article to be evaluated titled “A Learning Experience in Inquiry-Based Physics with Immersive Virtual Reality: Student Perceptions and an Interaction Effect Between Conceptual Gains and Attitudinal Profiles” that was published in the Journal of science education and technology states as main educational impacts on education, the conceptual learning gains are meaningful and result in several implications in terms of instructional design and immersive VR integration in the classroom. Furthermore it argues that students with high science- and digital technologies–related attitudes seem to benefit more in the context of the learning design that was structured around an immersive VR simulation, compared to the low-attitude students.

The third article to be evaluated titled “The Effect of Physical and Virtual Inquiry-Based Experiments on Students’ Attitudes and Learning” that was published in the Journal of Science Education and Technology lists as two main educational impacts the fact that VLs can be used interchangeably with PLs, regarding the conceptual understanding and that students previous PL experience in a topic can be considered to be an important factor in the evaluation between VL and PL.

4.1.4. *Inclusion aspects*

In the studies reviewed, aspects such as gender inclusion, educational needs, or broader inclusion considerations like accessibility for students with disabilities are not explicitly addressed. In the article “A Learning Experience in Inquiry-Based Physics with Immersive Virtual Reality: Student Perceptions and an Interaction Effect Between Conceptual Gains and Attitudinal Profiles” the participants were higher education faculty and HE leaders.

4.1.5. *Key challenges*

Key challenges in the implementation of virtual and remote laboratories include the following:

Students’ familiarity with some topics may lead to not significant differences in the evaluation between physical vs virtual labs.

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The studies did not measure student characteristics and traits (e.g. inquiry- based skills, collaboration skills or immersive tendencies) on students perceived learning experiences and conceptual learning gains.

Future studies could replicate this research using different learning-experience designs with other types of immersive VR simulations, as well as focusing on students of different ages and in different domains to examine the consistency of the reported findings in other contexts and settings.

Future studies can be also enriched with the collection of qualitative data via observations of the learning process as well as students' interviews on their perceptions, which can be used for triangulation purposes.

Other studies in the same direction could further explore 'how' immersive VR simulations should be integrated in other phases of inquiry-based learning cycles and what could be the effects of alternative instructional designs on students' learning gains and their perceptions of the learning experience

The successful integration of VR/AR technologies is contingent upon overcoming several barriers, including the need for robust policy frameworks, strategic implementation methodologies, and enduring institutional preparedness. Challenges to execution include the necessity for enhanced professional development and infrastructure resources to facilitate effective VR/AR implementation.

4.2. Greece

In the search that was conducted in the Web of Science database, 82 articles were identified with the use of the keywords combination "Virtual Labs" AND "Biology Education" N= 13 / "STEM Education" N= 13 / "Health Education. N= 56". Of these, 31 were theoretical and were excluded according to pre-set criteria, and 51 were empirical. But only 11 empirical articles met the inclusion criteria of evaluating the use and learning impact of virtual laboratories in university-level settings. Thus, these 11 studies formed the final corpus for Greece analysis.

4.2.1. Current practices

Virtual labs have been applied in Greece across various domains, including biology, biomedical education, cognitive enhancement, and surgical training. Onlabs, a virtual microscopy system, has been utilized extensively in biology education to simulate lab procedures typically conducted using a microscope (Paxinou et al., 2020). Other innovations include virtual patient simulations for medical education (Dafli et al., 2023), and completely immersive VR instruments applied both in forensic molecular biology (Ewais et al., 2024) and cognitive therapy (Amprasi et al., 2022).

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4.2.2. Methodologies and type of activities

Greek VLs track the learning activities in the form of primarily structured and closed types, i.e., microscopy and follow-along procedure simulations. However, evidence of exploratory aspects, particularly in those platforms combining virtual with face-to-face tutorials, is found (Paxinou et al., 2020). The methodologies range from pre-post evaluation with control groups to IRT-based modeling for the assessment of learning gains (Paxinou et al., 2021). Interactive VR experiences, such as on molecular biology and on surgical simulations, incorporated active participation through motion control and avatar-supported sequences.

4.2.3. Impact on student learning

Evidence from studies demonstrate favorable outcomes. In microscopy, use of VL improved not just learning but also self-efficacy and time efficiency in skill execution (Paxinou et al., 2020). Antonelli et al. (2023) observed that hybrid environments increased learner motivation and engagement. In forensic molecular biology, learning satisfaction increased through VR simulation compared to the traditional method (Ewais et al., 2024). Equally, improved attention in children was observed after repeated VR sessions (Amprasi et al., 2022), confirming the functionality of immersive VLs in perceptual and cognitive training.

4.2.4. Inclusion aspects

Although a few of the articles fail to segment findings by gender or ability, others respond indirectly to accessibility. Kaufhold & Steinert (2024) note the potential of VR for visually impaired students, and Dafli et al. (2023) refer to virtual patients to assist learners amid COVID-19, ensuring continuity for remote or vulnerable learners.
Nevertheless, extensive inclusion plans remain to be routinely incorporated into Greek VL implementations.

4.2.5. Challenges and difficulties

The universal barriers are insufficient institutional infrastructure to accommodate immersive VR, poor faculty training, and little national policy regarding VL integration. In surgical and ophthalmology education, for example, haptic limitations lower the generalizability of skills from VR to real-world environments (Chatziralli et al., 2021). Moreover, even though Greek universities increasingly integrate VLs, software standardization and language localization remain issues that plague the system, particularly in interdisciplinary courses.

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4.3. Spain

In the search conducted in the Web of Science database, 160 articles were identified using the keyword combination “Virtual Labs” AND “Biology Education” (N=51) / “STEM Education” (N=13) / “Health Education” (N=96). However, most were not related to the topic of interest. Only 8 studies addressed the use of virtual laboratories in STEM education, 5 of which were theoretical and excluded based on the exclusion criteria. Ultimately, 3 articles were selected that met the criteria and evaluated the application of virtual laboratories in the classroom. It is important to note that many of the excluded articles focused on virtual reality and gamification. While these may provide relevant insights, they are not directly comparable to the use of virtual laboratories.

4.3.1. Current practices

Current practices related to virtual laboratories in the classroom are only specifically detailed in the article by Sierra et al. (2020), which explores the Spanish experience with the Go-Lab project (Global Online Science Labs for Inquiry Learning). This project focuses on implementing virtual and remote laboratories to enhance inquiry-based learning (IBL) in STEM education, particularly for secondary and high school students. It offers more than 500 online laboratories (both virtual and remote) and over 40 supporting applications to guide the experimental process. Although the project is predominantly implemented at the pre-university level, its remote and virtual laboratories could be adapted for university-level STEM education, providing structured environments for experimentation and hypothesis testing. By 2020, Go-Lab had reached a total of 281 Spanish schools, with approximately 25% of teachers actively developing and implementing it in their educational centres.

Two of the articles do not present virtual laboratories in the traditional sense but instead propose educational resources on online platforms to promote STEM education (Bakkum et al., 2022; Boada et al., 2022). These provide insights into other digital tools for interactive education in health sciences and STEM. The TAECon platform, whose virtual scenarios align with some characteristics of virtual laboratories, has been widely used, involving over 1,000 students and 50 secondary schools.

4.3.2. *Methodologies and type of activities*

Regarding the methodologies or types of activities used, the platforms presented in the articles by Bakkum et al. (2022) and Boada et al. (2022) include tools such as gamification and decision support systems (e.g., limited decision-making options and time constraints). The focus is on problem-based learning (PBL) and resource sharing to enhance teaching practices. Students can interact with the platform through virtual game sessions, working individually or in groups, in either face-to-face or virtual modes.

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The laboratories within the Go-Lab project focus on promoting inquiry-based learning by providing tools for hypothesis generation, data collection, and analysis, making them particularly relevant for teaching STEM disciplines. The Inquiry Learning Spaces (ILS) framework used in Go-Lab fosters active and collaborative learning, emphasizing critical thinking and scientific attitudes.

4.3.3. Impact on learning

Go-Lab has had a clear impact on curriculum development, with its flagship being the development of inquiry-based activities (ILS) for both students and teachers, centered around their own scientific and laboratory experiences. Go-Lab's applications have been observed to facilitate students' virtual laboratory experiences, enabling them to take on the role of creators and investigators in their learning processes, thereby encouraging youth engagement with STEM disciplines. The TAECon platform has demonstrated effectiveness in increasing student interest in STEM through problem-based learning and gamification. However, Boada et al. (2022) do not report quantifiable impacts on learning outcomes. The other selected articles do not provide specific information regarding the impact of virtual laboratories on learning outcomes.

4.3.4. Inclusion aspects

In the studies reviewed, aspects such as gender inclusion, educational needs, or broader inclusion considerations like accessibility for students with disabilities are not explicitly addressed. However, the open-access resources of Go-Lab and its multilingual platform (available in 27 languages) make it accessible to a wide demographic. Furthermore, the modular nature of its laboratories allows educators to adapt content to students with varying levels of scientific proficiency and cultural backgrounds, indirectly supporting inclusive learning environments.

On the other hand, the TAECon platform incorporates eight main characters from diverse ethnicities and genders in its central storyline, promoting inclusion. This diversity aims to foster representation and engagement among students from various backgrounds. However, similar to the other cases, the article does not provide detailed information on addressing different aspects of inclusion.

4.3.5. Key challenges and difficulties

Key challenges in the implementation of virtual and remote laboratories include (Sierra et al., 2020; Boada et al., 2022):

1. **Teacher Training**: Significant efforts were required to train teachers in using VLs, designing Inquiry Learning Spaces (ILS), and integrating them into their

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teaching practices. Continuous support was necessary for educators to build confidence in implementing inquiry-based methods.

2. **Student Autonomy**: Inquiry-based learning demands that students take an active role in their education, which can be challenging for those accustomed to more guided learning approaches.
3. **Student Motivation**: One of the TAECon platform's goals was to address students' perception of STEM subjects as difficult by making learning engaging and relevant. However, the success of this strategy depends on how effectively the platform integrates real-world relevance into its challenges.
4. **Evaluation and Feedback Systems**: Teachers highlighted the need for robust evaluation tools and feedback mechanisms to monitor student progress effectively.
5. **Infrastructure**: Although virtual laboratories provide access to real experiments via the Internet, reliable infrastructure (e.g., stable Internet connections) remains a barrier in certain educational contexts.
6. **Scalability and Adaptability**: While TAECon is primarily designed for STEM promotion, adapting it to academic teaching contexts or extracurricular activities may require additional development and support.

Other key challenges identified in the study by Bakkum et al. (2022) include transitioning from traditional teaching methods (lecture-based and textbook-focused) to online and problem-based education, and the lack of resource-sharing among educators.

4.4. Romania

In the bibliographical analysis carried out for Romania, using the Web of Science database and the methodology established in the project, 22 articles were initially identified, of which 8 with a theoretical approach and 14 with an empirical one for the topics covered. In the second stage, the abstracts of the articles with empirical approach were analyzed, only two of them being selected for analysis, being related to the use of virtual activities or laboratories in STEM or medical education.

4.4.1. Current practices

Current practices in using VLs in STEM and health education have shown significant advancement and effectiveness, particularly highlighted by the articles "Impact of NEWTON Technology-enhanced Learning Solutions on Knowledge Acquisition in Pilots Involving Students with Hearing Impairments" (Bratu et al., 2023) and "Teaching resources for the European Open Platform for Prescribing Education (EurOP2E)—a nominal group technique study" (Bakkum et al., 2022).

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The methodologies described by Bratu et al. (2023) involved the deployment of Virtual Reality (VR) and Virtual Laboratory (VL) technologies within game-based learning frameworks to teach STEM-related content. Specifically, the study focused on students with hearing impairments, employing avatars for sign language translation and providing sensory-rich, interactive experiences through applications such as the "Wildlife" and "Sealife" educational games. These platforms allowed students to explore natural habitats virtually and engage in detailed learning activities about various animals through interactive quizzes and exploratory tasks. The effectiveness of these methods was evaluated through pre-tests, mid-term assessments, and post-tests, comparing traditional teaching methods with mixed VL and traditional methods.

The activities in the NEWTON project, as described by Bratu et al., encompassed interactive learning scenarios where students navigated virtual environments, observed animals in immersive contexts, and completed associated tasks and quizzes to reinforce learning. The integration of gamification elements was designed to foster motivation, active participation, and enhanced engagement, significantly supporting students with special educational needs, such as hearing impairments, by providing accessible and inclusive educational content.

The impact of VLs demonstrated substantial improvements in knowledge acquisition among students with hearing disabilities. The findings indicated significant academic gains when VL technologies were combined with traditional teaching methods, showcasing that a mixed-method approach enhanced the depth of learning and student engagement. The students who experienced the combination of VLs and traditional methods scored notably higher in post-test evaluations compared to those receiving traditional instruction alone, confirming the efficacy of immersive, interactive technologies in special education contexts.

In parallel, the EurOP2E project reported by Bakkum et al. (2022) highlighted the necessity for high-quality, problem-based online teaching materials in health education, particularly for clinical pharmacology and therapeutics (CPT). Using a nominal group technique, educators across Europe collaboratively identified essential resources and methodologies for enhancing online prescribing education. This approach emphasized creating real-world, problem-based prescription scenarios, incorporating multimedia knowledge resources (such as clips and podcasts), and addressing topical and ethical prescribing issues. The project also underscored the importance of personalized medicine and evidence-based medicine in educational content.

Activities proposed by EurOP2E included scenario-based learning, interactive online case discussions, gamification, and decision-support tools designed to reflect real clinical decision-making environments. These activities were aimed not only at improving student preparedness in prescribing but also at facilitating professional

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development among educators through training resources, a repository of reusable exam questions, and the adoption of personalized formularies.

The impact of VLs as identified in EurOP2E revolved around their potential to significantly improve students' prescribing competencies by providing accessible, diverse, and context-rich learning resources. The collaborative creation and sharing of these resources across institutions were seen as crucial for standardizing and enhancing educational quality, particularly under the demands of remote learning imposed by the COVID-19 pandemic.

4.4.2. *Inclusion aspects*

Bratu et al. (2023) specifically addressed educational inclusion by targeting students with hearing impairments, recognizing the unique learning challenges faced by this group. The VL technologies in the NEWTON project incorporated multimodal content delivery methods, such as sign language avatars and haptic feedback, to support students' varying sensory and cognitive abilities. This customization was designed to reduce barriers and improve access to complex STEM content. Moreover, the study considered gender by including balanced gender representation within participant groups, demonstrating awareness of gender inclusivity in educational technology deployment.

Furthermore, the study highlighted the importance of personalized educational experiences tailored to individual learning capabilities, emphasizing that students with disabilities require specially designed educational content to ensure meaningful and inclusive participation. These efforts aimed at bridging educational gaps, facilitating equitable learning opportunities, and improving academic outcomes for students with special educational needs.

The EurOP2E project reported by Bakkum et al. (2022) primarily focused on inclusive education through international collaboration and the sharing of resources across diverse European contexts. While the study did not explicitly discuss gender inclusion, it emphasized creating adaptable educational materials that cater to diverse educational needs and regional differences. The project underscored the significance of developing problem-based learning resources that are universally applicable and sensitive to local contexts, thus promoting broader educational inclusion.

The EurOP2E study also discussed inclusivity in terms of digital readiness among educators. By proposing professional development and continuous training, the project aimed to support educators in adopting and effectively utilizing new educational technologies, thereby indirectly facilitating inclusivity by ensuring teachers are well-prepared to address diverse student needs within virtual learning environments.

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4.4.3. Key challenges

According to Bratu et al. (2023), significant challenges in VL implementation include infrastructure issues such as ensuring reliable access to high-quality technological resources (e.g., VR headsets, adequate PCs, and stable internet connections). These infrastructural requirements can be particularly demanding for institutions with limited financial resources, affecting their capability to implement advanced technologies uniformly across educational settings. Furthermore, technical challenges such as providing effective sensory feedback and maintaining seamless integration of avatars for accessibility, particularly sign language translation, were identified as crucial yet complex features necessary for supporting students with special educational needs.

Teacher training emerged as another substantial challenge in the NEWTON project. The teachers required extensive training sessions to effectively utilize VL and VR technologies in classrooms, suggesting a steep learning curve and a need for dedicated professional development. Teachers had to acquire not only technical skills but also adapt pedagogical strategies to integrate game-based learning effectively, thus highlighting the necessity for continuous support and training to maintain the efficacy of VL-based education.

Educational needs posed specific challenges as the educational content had to be carefully designed to accommodate diverse learning requirements, especially for students with hearing disabilities. Bratu et al. underscored the importance of customized educational content that avoids cognitive overload and maximizes accessibility through multimodal delivery (visual, auditory, haptic).

In the EurOP2E project, Bakkum et al. (2022) also identified several critical challenges. A major difficulty was related to the digital readiness of educators, who often resisted transitioning from traditional methods to problem-based online learning due to lack of familiarity or reluctance to change established teaching habits. This resistance underscores the significant need for targeted faculty development and ongoing pedagogical support to facilitate the adoption of new technologies.
Another challenge highlighted was the standardization and compatibility of resources across international settings. Differences in national guidelines, regulations, and prescribing practices posed barriers to creating universally applicable educational materials, requiring the development of adaptable resources sensitive to regional contexts.

Furthermore, logistical issues around the collaborative creation and sharing of online resources were also noted. The study reported that despite willingness, educators rarely shared their resources internationally due to a lack of suitable platforms, highlighting infrastructural and logistical gaps that need addressing to foster greater resource sharing and collaboration.

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5. Literature review findings from other European countries

This section will include a table with all data obtained and a brief overview and brief description of the main findings displayed in the table by country.

5.1. Finland

In the search conducted using EPIC Database, UNIC Local Database of Digital Library and Google scholar database, a large number (over 200) of articles were identified using the keyword combination “Virtual Labs” AND “Biology Education” / “STEM Education” / “Health Education”. However, most were not related to the topic of interest, or they were not related to Finland and excluded based on the exclusion criteria. Ultimately, 4 articles were selected that met the criteria and evaluated the application of virtual laboratories in the classroom.

The four articles (2- 5) will be analysed in the respective tables:

1. A Virtual Reality Laboratory for Blended Learning Education: Design, Implementation and Evaluation https://www.mdpi.com/2227-7102/13/5/528
2. Student experiences from virtual reality-based chemistry laboratory exercises https://www.sciencedirect.com/science/article/pii/S1749772823000295
3. Enhancing 360° virtual laboratory safety training with linear learning pathway design: Insights from student experiences https://www.sciencedirect.com/science/article/pii/S1749772824000034
4. Digital Labs as a Complement to Practical Laboratory Training for Bachelor and Master Biomedicine Students https://ceur-ws.org/Vol-3393/TELL23_paper_9410_1.pdf

Table 2. *Findings from the paper by Antonelli et al, 2024.*

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QUESTIONS	ANALYSIS	
Type of activity	OPEN / CLOSE	**Closed:** The activities in the study are structured and the students have to follow specific inquiry tasks
	ACTIVE / PASSIVE	**Passive**: There are not any interactive activities
	CONTEXT	**Real-life context**
	INDIVIDUAL	The activities are carried out **individually.**
Methodologies used	Interactive	The methodologies are interactive, as students actively interact with both the environment and the informational texts, requiring continuous engagement and critical thinking.
Impact on learning	Positive	Students maintained a positive attitude toward learning
Difficulties identified	1) Duration of the VR training and the complexity of the subject matter. 2) Not the same level regarding the comprehension of the English language.	
Inclusion aspects	No	
Needs	Need for **scaffolding** to help students effectively relate the informational texts to activities. The study also emphasizes the importance of **training teachers** to implement these integrated approaches effectively.	
Educational implications	1) Students maintained a positive attitude toward the VR workshop before and after the experience. 2) The level of difficulty was negatively associated with motivation	

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Table 3. *Findings from the paper by* Viitaharju et al., 2023.

QUESTIONS	ANALYSIS	
Type of activity	OPEN / CLOSE	**Both open and closed:** Some of the activities are structured and the students have to follow specific inquiry tasks and some of the activities in the study are open-ended, allowing students to explore virtual labs.
	ACTIVE / PASSIVE	**Passive**: There are not any interactive activities
	CONTEXT	**Real-life context**
	INDIVIDUAL	The activities are carried out **individually**, although they could potentially be adapted for group settings
Methodologies used	Interactive	The methodologies are interactive, as students actively interact with both the environment and the informational texts, requiring continuous engagement and critical thinking.
Impact on learning	Positive	The study identifies a **positive** impact on learning, particularly in enhancing students' understanding of scientific concepts and their ability to integrate knowledge from different sources (texts and experiments).
Difficulties identified	With current level of technology virtual contents should be considered as supplemental supporting learning materials for real-life laboratories, not as a substitute to real-life laboratories	
Inclusion aspects	No. The participating students were randomly divided into two groups	

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Needs	Need to do both the as well as the real-life lab.
Educational implications	1) Virtual laboratory also offers a possibility to add elements such as activating questions to the laboratory work which might be difficult to execute as precisely in a real laboratory 2) students clearly prefer having more interactive learning content such as questions and videos rather than traditional text and images.

Table 4. *Findings from the paper by* Girmayet al., 2024.

QUESTIONS	ANALYSIS	
Type of activity	OPEN / CLOSE	**Closed:** The activities in the study are structured and the students have to follow specific inquiry tasks
	ACTIVE / PASSIVE	**Passive**: There are not any interactive activities
	CONTEXT	**Real-life context**
	INDIVIDUAL	The activities are carried out **individually**,
Methodologies used	Interactive	The methodologies are interactive, as students actively interact with both the environment and the informational texts, requiring continuous engagement and critical thinking.
Impact on learning	Positive	The study identifies a **positive** impact on learning,
Difficulties identified	Duration of the VR training and the complexity of the subject matter.	
Inclusion aspects	No	

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Needs	Need for teacher guidance and to implement these integrated approaches effectively.
Educational implications	The effectiveness of the design of the virtual laboratory in promoting motivation, engagement and understanding of the particular scientific aspect.

Table 5. *Findings from the paper by* Cheung al., 2023.

QUESTIONS	ANALYSIS	
Type of activity	OPEN / CLOSE	**Both Open and closed:** Some of the activities are structured and the students have to follow specific inquiry tasks and some of the activities in the study are open-ended, allowing students to explore virtual labs
	ACTIVE / PASSIVE	**Active**: There are interactive activities
	CONTEXT	**Real-life context**
	INDIVIDU AL	The activities are carried out in group settings
Methodologies used	Interactive	The methodologies are interactive, as students actively interact with both the environment and the informational texts, requiring continuous engagement and critical thinking.

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Impact on learning	Positive	Students maintained a positive attitude toward learning
Difficulties identified	Digital laboratories, in their current form, have limited capability to support teamwork and interactions between students, which are typically part of real-life laboratory sessions. The effect of digital laboratories on self-reported interest was smaller compared to their impact on understanding and integration of theory and practice. The distribution of responses regarding the integration of theory and practice was wider, indicating variability in perceived benefits.	
Inclusion aspects	No	
Needs	There is a need to evaluate the impact of digital simulations on students' learning post-pandemic and to perform a cost-benefit analysis to understand their effectiveness and efficiency. Learning analytics (LA) could be further utilized to analyze and support learning in virtual laboratories, providing insights into how learning occurs in digital environments.	
Educational implications	Digital laboratories offer diversity in learning methods and can enhance students' interests and knowledge acquisition. They provide useful insights for course design in university STEM courses. The integration of learning analytics with virtual laboratory programs is of great interest for the future, as it can help identify difficult concepts and inform decisions on educational tools for future generations. Despite their benefits, digital laboratories should be used under the right conditions to maximize their educational impact, as they currently show only a medium effect size on student achievement.	

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5.1.1. Summary of key findings

The integration of VLs in STEM and health education has progressed at different rates across European countries, reflecting varying levels of digital infrastructure, institutional readiness, and faculty expertise. While some nations have successfully implemented VLs as core components of experimental learning, others face significant barriers to adoption.

In countries like Finland, VLs are already well-integrated into biology, chemistry, and medical training, providing students with interactive and engaging learning experiences. Studies highlight that VLs contribute positively to self-regulated learning, conceptual understanding, and knowledge retention. However, challenges remain, particularly with language barriers, as many Virtual Laboratory (VL) platforms are primarily developed in English, limiting accessibility for non-native speakers and potentially affecting student engagement and comprehension.

Additionally, while VLs support procedural learning, not all platforms incorporate highly interactive components, limiting the extent of student-driven exploration and experimentation. Conversely, in Cyprus, VL adoption remains in its early stages, with only a few documented studies exploring their use in higher education. While secondary education efforts have piloted inquiry-based learning through virtual labs, their adaptation to university-level curricula is still limited. Institutional readiness varies, as some faculty members recognize the potential of VLs, yet standardized policies, evaluation frameworks, and structured investments are lacking. Without dedicated funding and faculty training programs, the scalability and long-term sustainability of VLs in Cyprus remain uncertain.

Similarly, Estonia has yet to fully embrace VLs in higher education, as the literature on their use remains largely theoretical rather than grounded in practical implementation. Despite Estonia's strong emphasis on digital education, particularly at the primary and secondary levels, higher education institutions struggle with digital infrastructure limitations and a lack of faculty training in VL integration. The absence of empirical studies on VL adoption in Estonian universities indicates the need for further research and investment in this area.

Across all three countries, a common challenge is the need for faculty development and policy support to facilitate the effective integration of VLs into curricula. While Finland demonstrates advanced adoption, Cyprus and Estonia require targeted interventions to build institutional capacity, improve digital infrastructure, and develop structured policies that promote VL sustainability in higher education.

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5.1.2. Recommendations

To ensure the effective adoption and integration of VLs in STEM and health education, the following strategic actions are recommended:

Strengthening faculty training and support

- Develop targeted professional development programs to equip educators with the necessary skills to implement and assess VL-based learning.
- Establish a centralized knowledge-sharing platform where institutions can exchange best practices, instructional strategies, and case studies on VL integration.
- Provide technical and pedagogical support for faculty to ensure effective utilization and adaptation of VLs across various disciplines.

Investing in digital infrastructure and accessibility

- Increase funding for digital infrastructure to ensure that higher education institutions have the necessary resources to support VL expansion.
- Develop multilingual and adaptive VL content to enhance accessibility for non-native speakers and diverse student populations.
- Implement user-friendly interfaces and inclusive design principles to cater to students with different learning needs and abilities.

Developing standardized guidelines for VL implementation

- Establish evaluation frameworks to assess the effectiveness of VLs in improving student engagement, learning outcomes, and practical skills development.
- Encourage cross-border collaborations to develop and share open-access VL resources, fostering scalability and sustainability across institutions.
- Develop institutional policies that integrate VLs into curricula, ensuring consistent and structured implementation within higher education programs.

Encouraging research and policy support

- Conduct longitudinal studies on the impact of VLs on student motivation, academic performance, and career readiness to inform future improvements.
- Advocate for policy frameworks that embed VLs into national STEM and digital education strategies, ensuring higher education institutions receive ongoing support and funding.
- Promote partnerships between universities, technology providers, and policymakers to create a sustainable ecosystem for VL adoption and innovation.

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Implementing these recommendations will help VLs evolve into a powerful educational tool, significantly enhancing experimental learning, improving accessibility, and equipping students with essential skills for careers in STEM and health sciences.

5.2. Estonia

In the search conducted in EPIC Database, UNIC Local Database of Digital Library and Google scholar database, a small number (less than 30) of articles were identified using the keyword combination “Virtual Labs” AND “Biology Education” / “STEM Education” / “Health Education”. However, most were not related to the topic of interest, or they were not related to Estonia and excluded based on the exclusion criteria. Two articles addressed the use of virtual laboratories in STEM education but were theoretical and excluded based on the exclusion criteria.

Virtual Laboratories hold significant potential in enhancing STEM and health education by making experimental learning more accessible, flexible, and engaging. While Finland demonstrates advanced adoption, Cyprus and Estonia face implementation challenges related to infrastructure, faculty training, and research gaps. Strategic investments, faculty development, and standardized guidelines are essential for scaling VLs across higher education institutions and ensuring their effective integration into curricula.

By addressing these key challenges and leveraging best practices, Virtual Laboratories can bridge the gap between theoretical knowledge and practical application, equipping students with the digital skills necessary for future careers in STEM and health sciences.

5.3. Bulgaria

17 articles were detected in the Web of Science database search conducted via the keyword selection "Virtual Labs" AND "Biology Education" N= 6 / "STEM Education" N= 2 / "Health Education N= 9." Of these, 7 were theoretical and were excluded following the pre-formulated exclusion standards. The remaining 10 studies were empirical research. However, all these studies failed to meet the final set of inclusion criteria of measuring the implementation and impacts of virtual laboratories on university classroom levels. Therefore, 0 articles were included for final analysis in Bulgaria.

5.4. Germany

In the Web of Science database search, 289 articles were identified using the keyword term combination "Virtual Labs" AND "Biology Education" N= 118 / "STEM Education" N= 27/ "Health Education N= 144." Of these articles, 82 were theoretical and thus excluded per exclusion criteria, and 207 were empirical. Out of these empirical studies,

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however, only 18 empirical articles met the criteria, as the objective in reviewing learning gains was to seek concrete outcomes. Thus, these 18 articles formed the last corpus of German analysis.

Table 6 displays a quantitative summary of the results. It has to be highlighted that the numbers included correspond to the total number of articles reporting on each of the dimensions analyzed. The same article can include various types of activities or methodologies. Therefore, for instance, open and closed activities can appear in the same article and would accordingly be listed in both categories.

Table 6. Quantitative findings from Germany. Numbers represent the number of articles reporting each characteristic.

QUESTIONS	DATA ANALYSIS	YES	NO	LIMITED	NOT REPORTED
Type of activities	Open	3	9	2	4
	Closed	17	0	1	0
	Active	18	0	0	0
	Passive	5	4	9	0
	Contextualised	14	0	0	4
	Non-Contextualised	0	14	0	4
	Group	7	5	0	6
	Individual	16	2	0	0
Methodologies used	Interactive	18	0	0	0
	Non - interactive	4	1	13	0
Impact on learning	Positive	18	0	0	0
	Negative	10	5	3	0
Inclusion aspects addressed		5	8	5	0

5.4.1. Existing practices

Germany illustrates an advanced stage of VLs adoption at tertiary level, particularly in STEM and healthcare studies. The reviewed literature exhibits a very wide variety of VL uses in biology, engineering, neuroscience, nursing, and health science education. For instance, the VIDAR Lab offers a project-oriented networking lab (Karal et al., 2022), while EnLighten offers interactive solar cell simulations (Arntz et al., 2021). VR applications were also used in neuroscience (Formella-Zimmermann et al., 2022),

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control systems (Prohaska & Kennes, 2023), robotics (Bunse & Wieck, 2022), and histology (Hänni et al., 2024).

5.4.2. Methodologies and type of activities

Most of the activities follow a pre-structured (closed) format; however, some provide opportunities for open-ended problem solving. Students have a range of simulated activities- from operating virtual instruments to performing cognitive activity in gamified spaces. Of particular interest are studies employing mixed methods of designs, including performance analytics, surveys, and qualitative assessments. For example, Formella-Zimmermann et al. (2022) compare the student experience of neuroscience in virtual and practical labs with discovering positive motivational trends. Müller et al. (2021) assess technology acceptance for cell biology learning via VR, in turn.

5.4.3. Impact on student learning

Empirical findings show a consistently positive impact on learning outcomes. VR-based VLs improved cognitive retention, practical skill learning, and conceptual understanding. Bauermeister et al. (2024) determined that biology students who were educated using e-learning outperformed students who were educated using traditional methods. Similarly, Plotzky et al. (2023) demonstrated that nursing students who were educated using VR simulation were more skilled in complex procedures. Improvement of learning was also found in distant engineering laboratories (Bunse et al., 2023) and VR games for safety training (Hänni et al., 2024).

5.4.4. Inclusion aspects

Though there are no separate results reported for disability or gender in most research, there are a few focused specifically on inclusivity. Kaufhold & Steinert (2024) describe the application of haptic VR to visually impaired students, with enhanced accessibility. Kim et al. (2021) describe telerehabilitation for individuals with aphasia, with advantages of VR in virtual therapeutic environments. These illustrate the potential of VLs to combat traditional access barriers in STEM and health learning.

5.4.5. Key challenges

Shared implementation challenges include infrastructure insufficiency, software volatility, low haptic realism, and costly development. Technical support and instructor training are given a high priority by research (Gruenewald et al., 2021; Bunse et al., 2023). Some articles, such as Dormegny et al. (2024), assert that although there is potential in VR simulation, it is still not capable of simulating the haptic experience

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necessary in surgical training to the same degree. In addition, different levels of technological competence between both students and personnel remain an impediment to its implementation.

5.5. France

In the bibliographical analysis carried out for France, using the Web of Science database and the methodology established in the project, 148 articles were initially identified, of which 61 with a theoretical approach and 87 with an empirical one for the topics covered. In the second stage, the abstracts of the articles with empirical approach were analyzed, only three of them being selected for analysis, being related to the use of virtual activities or laboratories in STEM or medical education.

Table 7. Findings from the paper by Agarwal et al. (2021).

QUESTIONS	DATA ANALYSIS	
Type of activities	OPEN / CLOSE	**Open:** The activities provide open questions that students need to solve.
	ACTIVE / PASSIVE	**Active**: There are interactive activities.
	CONTEXT	Real-life context
	GROUP	-
	INDIVIDUAL	-
Methodologies used	Interactive	Web-based educational model for training in semen analysis, emphasizing an interactive format featuring video demonstrations, live lectures, and interactive troubleshooting sessions
	Non - interactive	No
Impact on learning	Positive	Yes. Reported high satisfaction among participants in online semen analysis training, noting that the digital format met or exceeded participant expectations
	Negative	No
Difficulties identified	Echnical issues, including limited access to advanced technologies, inadequate internet connectivity, and the costs of software and hardware as significant barriers	
Inclusion aspects	Demonstrated inclusivity by offering global access to specialized training irrespective of geographical location, thus addressing international educational disparities	

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Needs	the need for better training of trainers and investment in technological resources
Educational implications	-

Table 8. Findings from the paper by Chatziralli et al. (2021).

QUESTIONS	DATA ANALYSIS	
Type of activities	OPEN / CLOSE	**Open:** The activities provide open questions that students need to solve.
	ACTIVE / PASSIVE	**Active**: There are interactive activities.
	CONTEXT	Real-life context
	GROUP	-
	INDIVIDUAL	-
Methodologies used	Interactive	Discussed ophthalmic education during the COVID-19 pandemic, where traditional teaching methods transitioned significantly to virtual platforms, employing interactive web-based sessions through platforms such as Zoom.
	Non - interactive	No
Impact on learning	Positive	Indicated that virtual ophthalmology education effectively maintained theoretical training standards during the pandemic, although practical surgical training suffered significant reductions, negatively impacting overall training quality.
	Negative	No
Difficulties identified	Challenges in practical training, indicating that surgical training faced severe limitations due to virtual formats not adequately replacing hands-on experience	
Inclusion aspects	No	

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Needs	Need for effective virtual practical training solutions to supplement theoretical online education
Educational implications	-

Table 9. Findings from the paper by Decormeille et al. (2022).

QUESTIONS	DATA ANALYSIS	
Type of activities	OPEN / CLOSE	**Open:** The activities provide open questions that students need to solve.
	ACTIVE / PASSIVE	**Active**: There are interactive activities.
	CONTEXT	Real-life context
	GROUP	-
	INDIVIDUAL	-
Methodologies used	Interactive	Screen-based simulations (SBS) in nursing education, utilizing interactive computer-based scenarios designed to enhance clinical reasoning, decision-making, and leadership skills. SBS allowed learners to engage in scenarios actively and included mandatory debriefing sessions.
	Non - interactive	No
Impact on learning	Positive	Found SBS effective in complementing traditional nursing education, enhancing cognitive and decision-making skills without replacing practical clinical training.
	Negative	No
Difficulties identified	Technical issues, including limited access to advanced technologies, inadequate internet connectivity, and the costs of software and hardware as significant barriers	
Inclusion aspects	Smaller and medium-sized institutions often struggled to implement SBS due to resource limitations, indirectly addressing economic inclusion	
Needs	The need for better training of trainers and investment in technological resources	
Educational implications	-	

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5.5.1. Methodologies used

Decormeille et al. (2022) described screen-based simulations (SBS) in nursing education, utilizing interactive computer-based scenarios designed to enhance clinical reasoning, decision-making, and leadership skills. SBS allowed learners to engage in scenarios actively and included mandatory debriefing sessions.

Agarwal et al. (2021) detailed a web-based educational model for training in semen analysis, emphasizing an interactive format featuring video demonstrations, live lectures, and interactive troubleshooting sessions. This model also utilized assessments through multiple-choice questions.

Chatziralli et al. (2021) discussed ophthalmic education during the COVID-19 pandemic, where traditional teaching methods transitioned significantly to virtual platforms, employing interactive web-based sessions through platforms such as Zoom.

5.5.2. Impact on learning

All studies indicated positive impacts on learning outcomes, primarily due to enhanced accessibility, interactivity, and personalized learning experiences. Decormeille et al. (2022) found SBS effective in complementing traditional nursing education, enhancing cognitive and decision-making skills without replacing practical clinical training. Agarwal et al. (2021) also reported high satisfaction among participants in online semen analysis training, noting that the digital format met or exceeded participant expectations.

Chatziralli et al. (2021) indicated that virtual ophthalmology education effectively maintained theoretical training standards during the pandemic, although practical surgical training suffered significant reductions, negatively impacting overall training quality.

5.5.3. Difficulties identified

Infrastructure challenges were common across studies. Decormeille et al. (2022) and Agarwal et al. (2021) cited technical issues, including limited access to advanced technologies, inadequate internet connectivity, and the costs of software and hardware as significant barriers.

Chatziralli et al. (2021) underscored the challenges in practical training, indicating that surgical training faced severe limitations due to virtual formats not adequately replacing hands-on experience.

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5.5.4. Inclusion aspects

The studies addressed inclusion, considering educational needs and, to some extent, gender aspects. Decormeille et al. (2022) noted that smaller and medium-sized institutions often struggled to implement SBS due to resource limitations, indirectly addressing economic inclusion.

Agarwal et al. (2021) demonstrated inclusivity by offering global access to specialized training irrespective of geographical location, thus addressing international educational disparities.

Gender inclusion was not explicitly detailed across all studies but was implicitly present through balanced participant demographics where mentioned.

5.5.5. Identified needs

A common need across studies was improved technical infrastructure, extensive educator training, and ongoing support. Decormeille et al. (2022) and Agarwal et al. (2021) specifically highlighted the need for better training of trainers and investment in technological resources.

Chatziralli et al. (2021) highlighted the critical need for effective virtual practical training solutions to supplement theoretical online education.

5.5.6. Educational implications

These studies collectively underscore critical educational implications. Interactive virtual learning environments significantly enhance engagement, motivation, and learning outcomes. However, reliance solely on virtual formats could negatively impact practical skill development, particularly in clinical disciplines.

There is a clear implication for future educational strategies to adopt hybrid models that combine traditional practical training with robust virtual interactive methodologies. Continuous professional development and resource sharing platforms are crucial to ensuring educators effectively implement and benefit from advanced virtual teaching methods.

5.6. Portugal

In the bibliographical analysis carried out for Portugal, using the Web of Science database and the methodology established in the project, 80 articles were initially identified, of which 39 with a theoretical approach and 41 with an empirical one for the topics covered. In the second stage, the abstracts of the articles with empirical

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approach were analyzed, only two of them being selected for analysis, being related to the use of virtual activities or laboratories in STEM or medical education.

Table 10. Findings from the paper by Padilha et al. (2024).

QUESTIONS	DATA ANALYSIS	
Type of activities	OPEN / CLOSE	**Open:** The activities provide open questions that students need to solve.
	ACTIVE / PASSIVE	**Active**: There are interactive activities.
	CONTEXT	Real-life context
	GROUP	-
	INDIVIDUAL	-
Methodologies used	Interactive	Utilized clinical virtual simulations (CVS), which immerse nursing students in realistic patient scenarios through virtual platforms
	Non - interactive	No
Impact on learning	Positive	Nursing students reported high levels of perceived usefulness, ease of use, and behavioral intention to use, demonstrating robust acceptance
	Negative	No
Difficulties identified	Challenges related to cognitive load and varying complexity of clinical scenarios	
Inclusion aspects	Focused on broad acceptance among diverse student groups without explicitly highlighting gender differences, suggesting a universal design approach to inclusivity	
Needs	Need for adaptive difficulty in simulations to match students' evolving competencies and prevent cognitive overload	
Educational implications	CVS adoption requires curriculum redesign and continuous educator training to leverage technology effectively for clinical skills training	

Table 11. Findings from the paper by Valentim et al. (2022).

QUESTIONS	DATA ANALYSIS	
Type of activities	OPEN / CLOSE	**Open:** The activities provide open questions that students need to solve.
	ACTIVE / PASSIVE	**Active**: There are interactive activities.

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	CONTEXT	Real-life context
	GROUP	-
	INDIVIDUAL	-
Methodologies used	Interactive	Discussed AVASUS, an open and interactive Virtual Learning Environment (VLE), which offers distance learning courses through a flexible online platform
	Non - interactive	No
Impact on learning	Positive	Substantial positive educational impact
	Negative	No
Difficulties identified	Technological infrastructure as a significant barrier, including limitations in internet connectivity and access to appropriate technology	
Inclusion aspects	Explicitly addressed regional inclusion	
Needs	Continued investment in technological infrastructure, enhanced user support, and extensive training programs to improve digital literacy among healthcare professionals	
Educational implications	Scalable platforms like AVASUS can meet nationwide training needs effectively	

5.5.7. Methodologies used

The methodologies used in both articles emphasize interactive educational approaches. Padilha et al. (2024) utilized clinical virtual simulations (CVS), which immerse nursing students in realistic patient scenarios through virtual platforms. This method enables students to practice clinical decision-making, critical thinking, and procedural skills in a controlled, risk-free environment. The Technology Acceptance Model 3 (TAM3) framework was employed to analyze user acceptance of virtual simulations, incorporating dimensions such as perceived usefulness, ease of use, and behavioral intentions.

Similarly, Valentim et al. (2022) discussed AVASUS, an open and interactive Virtual Learning Environment (VLE), which offers distance learning courses through a flexible online platform. This platform hosts courses developed collaboratively by health and educational institutions, integrating multimedia content, interactive web lectures, and modules specifically tailored to various public health emergencies such as COVID-19 and the Zika virus outbreak. The platform's effectiveness was assessed through participant surveys, highlighting its scalability and accessibility.

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5.5.8. Impact on learning

Both studies reported predominantly positive impacts on learning outcomes. Padilha et al. (2024) found that nursing students reported high levels of perceived usefulness (mean = 5.34/7), ease of use (mean = 4.74/7), and behavioral intention to use CVS (mean = 5.21/7), demonstrating robust acceptance. This positive acceptance was primarily attributed to the relevance of virtual simulations for learning and the enjoyability of the experience, contributing significantly to students perceived clinical competence and readiness.

Valentim et al. (2022) reported substantial educational impact through AVASUS, with 79.7% of participants confirming the platform facilitated knowledge sharing in their workplace, and 57.4% recognizing its enhancement of teamwork. Approximately 75.6% indicated that the courses directly contributed to improving existing health services, and 24.4% were enabled to offer new services following their training, underlining the platform's practical applicability and effectiveness.

5.5.9. Difficulties identified

Despite positive impacts, several implementation difficulties were identified. Padilha et al. (2024) noted challenges related to cognitive load and varying complexity of clinical scenarios, indicating a need for tailored difficulty levels to maintain student engagement and effectiveness of CVS.

Valentim et al. (2022) highlighted technological infrastructure as a significant barrier, including limitations in internet connectivity and access to appropriate technology. Additionally, the authors acknowledged variability in user digital literacy, emphasizing a need for more extensive training and resources to address these gaps and ensure equitable access and effective usage.

5.5.10. Inclusion aspects

Both studies implicitly addressed inclusion. Padilha et al. (2024) focused on broad acceptance among diverse student groups without explicitly highlighting gender differences, suggesting a universal design approach to inclusivity. However, the high acceptance rates across diverse demographics indicate broad applicability and potential inclusivity of CVS.

Valentim et al. (2022) explicitly addressed regional inclusion by providing accessible and free educational resources across Brazil's diverse geographic regions, thereby addressing educational inequalities and regional disparities in access to continuing education.

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5.5.11. Identified needs

Both articles underscore the critical needs for effective VL integration. Padilha et al. (2024) identified a need for adaptive difficulty in simulations to match students' evolving competencies and prevent cognitive overload. They also highlighted the necessity of increasing student support mechanisms, particularly for those with lower perceived self-efficacy.

Valentim et al. (2022) emphasized the necessity for continued investment in technological infrastructure, enhanced user support, and extensive training programs to improve digital literacy among healthcare professionals, ensuring effective and equitable use of AVASUS.

5.5.12. Educational implications

The implications from these studies strongly support integrating VL into healthcare education curricula. The findings suggest that virtual simulations significantly enhance critical skills required in clinical settings, thus improving overall preparedness and patient safety. They emphasize the importance of addressing infrastructure and user training needs to maximize effectiveness and inclusivity.

Padilha et al. (2024) imply that CVS adoption requires curriculum redesign and continuous educator training to leverage technology effectively for clinical skills training. Valentim et al. (2022) suggest that scalable platforms like AVASUS can meet nationwide training needs effectively, promoting lifelong learning and resilience in healthcare systems, especially in crisis situations.

5.7. The Netherlands

In the search conducted in the Web of Science database, 156 articles were identified using the keyword combination “Virtual Labs” AND “Biology Education” (N=31) / “STEM Education” (N=67) / “Health Education” (N=58). However, most were not related to the topic of interest.

After reviewing the abstracts, only one article could be related to the use of virtual laboratories in the classroom, as the remaining articles focused on different topics or on the use of virtual reality and gamification in education. While the information may be valuable for the development of educational guidelines or resources, these articles do not provide examples to illustrate the use of virtual laboratories in formal education in the Netherlands. The selected article belongs to the field of educational psychology and it investigates, through eye-tracking technology, the integration of informational

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texts and the use of virtual laboratories and how this influence inquiry-based learning (Van der Graaf, Segers, & de Jong, 2020).

Table 12. Findings from the paper by Van der Graaf, Segers, & de Jong (2020).

COUNTRY	QUESTIONS	ANALYSIS	
The Netherlands	**Type of activity**	OPEN / CLOSE	**Open:** The activities in the study are structured but open-ended, allowing students to explore virtual labs while guided by specific inquiry tasks
		ACTIVE / PASSIVE	**Active**: There are interactive activities
		CONTEXT	**Real-life context**
		INDIVIDUAL	The activities are carried out **individually**, although they could potentially be adapted for group settings
	Methodologies used	Interactive	Inquiry-based learning (IBL). The methodologies are interactive, as students actively interact with both the environment and the informational texts, requiring continuous engagement and critical thinking.
	Impact on learning	Positive	The study identifies a **positive** impact on learning, particularly in enhancing students' understanding of scientific concepts and their ability to integrate

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			knowledge from different sources (texts and experiments). However, the study also notes that while the integration of texts improves knowledge acquisition, it does not necessarily lead to better inquiry skills without additional scaffolding.
	Difficulties identified	One difficulty highlighted is the **cognitive load** associated with integrating texts and virtual labs, as students must navigate multiple sources of information simultaneously.	
	Needs	One challenge is the need for **teacher guidance and scaffolding** to help students effectively relate the informational texts to the activities. The study also emphasizes the importance of **training teachers** to implement these integrated approaches effectively.	
	Educational implications	• The findings suggest that combining informational texts with virtual labs can be a powerful approach to fostering scientific literacy and inquiry skills, especially in contexts where real-life experiments are not feasible. • The study underscores the importance of providing **scaffolding and support** to students during integrated tasks to maximize learning outcomes. • It also highlights the potential for applying this approach in **other STEM disciplines** and adapting it for diverse educational contexts.	

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5.6. Italy

In the search conducted in the Web of Science database, 211 articles were identified using the keyword combination “Virtual Labs” AND “Biology Education” (N=63) / “STEM Education” (N=16) / “Health Education” (N=132). Of the articles found, only five presented empirical results (“Biology Education” = 1, “STEM Education” = 2, “Health Education” = 3). However, despite being selected after reading the abstracts, none of the articles included in the field of Health education specifically address the use of virtual laboratories. Instead, they focus on augmented reality simulations or virtual educational platforms (Bagnasco et al., 2021; Bakkum et al., 2022; Menna et al., 2023). While the information may be valuable for developing educational guidelines or resources, these articles do not serve as examples to understand the use of virtual laboratories in formal education in Italy. Similarly, in the field of STEM education, only one article on virtual reality was evaluated, but it is not comparable to the use of virtual laboratories (Antonelli et al., 2023).

Only one study evaluates the role of the PhET virtual laboratory in the evolution of mental models among two groups of primary school students aged 9–10 years. In this study, practical and virtual activities were combined, with each group performing the activities in a different order to determine whether the sequence affected the evolution of their mental models (Bozzo et al., 2022). According to the article, although virtual activities improved the adequacy of students' responses in relation to the target model, this improvement did not transfer to new phenomena introduced. In other words, the ability to connect the developed model with the real world remained the same regardless of the sequence. The article concludes that simulations alone do not help students evaluate and refine their models, highlighting the need for teacher support in model-based teaching involving non-visible physical entities. Although it contains relevant information on the use of virtual laboratories, as it focuses on primary school, it is not analysed in detail in the table.

6. Transnational Comparison

This section provides a transnational comparative analysis of how Virtual Laboratories (VLs) are implemented and experienced across four EU partner countries: Cyprus, Greece, Spain, and Romania. As virtual and remote laboratory tools become increasingly important in higher education, particularly in STEM and health disciplines, understanding national approaches offers insight into both divergent practices and shared European priorities.

The comparative study draws upon national literature reviews and expert analyses conducted in each country. It considers not only the current state of VL deployment but also related factors such as pedagogical models, technological infrastructure, institutional readiness, and inclusion.

To visually support and summarise these insights, the accompanying infographic (see Figure 1) presents the most critical points across four core dimensions:

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- Comparative analysis of VL implementation by country, including national focus areas and representative technologies
- Common practices and methodologies, such as inquiry-based learning, gamification, and blended models
- Shared challenges, including infrastructure gaps, faculty readiness, and evaluation needs
- Good practices and transferable models, highlighting scalable or inclusive strategies applicable across different EU contexts

This visual tool is designed for rapid stakeholder understanding and offers a concise synthesis of the detailed findings.

Following this overview, each of the infographic's four sections is explored in-depth through structured narrative analysis, providing a comprehensive understanding of the comparative results across the partner countries. Each subsection (6.1 to 6.5) offers detailed insights supported by examples from national case studies, outlining both the diversity of approaches and the potential for coordinated European responses.

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Transnational Comparison

Comparative Analysis of the Use of Virtual Laboratories (VLs) in Partner Countries

Cyprus

- Limited implementation
- Focus on pre-university level
- Inquiry-based experiments
- Digital-readiness attitudes toward immersive technologies

Greece

- Widespread use in university-level STEM and health education
- Virtual-based VR simulations
- Pre/post assessments

Hybrid learning environments

Spain

- Large-scale deployment
- Go-Lab platform for secondary education
- Potential adaptation for higher education

Romania

- Targeted and specialized use
- Emphasis on inclusive education
- VR tools for hearing-mpined students
- Digital teaching materials for medical education

Common Practices and Methodologies

- Inquiry-based learning (IBL)
- Gamification and immersive technologies
- Hybrid and blended learning modeis

Common Challenges

- Lack of technological infrastructure
- Limited access toVR equipment
- Facuity training and digital readiness
- Standardized guidelines and evaluation tools

Good Practices and Transferable Models

- Go-Lab project in Spain
- VR for biomedical training
- Inclusive VLs for hearing-impaired

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Figure 1. Comparative insights on practices, challenges, and transferable models across EU partner countries.

6.1. Comparative analysis of the use of Virtual Laboratories (VLs) in partner countries

The use of VLs in STEM and health education varies significantly across the four partner countries, Cyprus, Greece, Spain, and Romania, reflecting differing institutional priorities, levels of technological infrastructure, and pedagogical strategies. Despite these contextual distinctions, several shared patterns and themes begin to emerge. The following subsection examines how VLs are currently being implemented in each national context, focusing on their scope of use, technological platforms, educational level of deployment, and degree of institutional integration.

In **Cyprus**, the implementation of VLs remains limited, with most studies focusing on pre-university settings. The work by Papalazarou et al. (2024) exemplifies early-stage integration through inquiry-based virtual experiments delivered via the Graasp platform. The focus was on comparing virtual and physical labs in conceptual learning and student attitudes. Other studies in Cyprus have explored broader themes such as digital readiness and student attitudes toward immersive technologies, suggesting that the groundwork is being laid for more systemic integration at the higher education level.

In contrast, **Greece** demonstrates a more mature and widespread use of VLs in university-level STEM and health education. Applications range from virtual microscopy (Onlabs) in biology courses to VR simulations for surgical training and cognitive enhancement. Methodologies often involve pre/post assessment designs, hybrid learning environments, and interactive VR-based modules that foster active participation. This diversity of applications reflects a well-established ecosystem that integrates virtual learning into regular curricular activities.

Spain presents a unique case with its large-scale deployment of VLs primarily in secondary education, particularly through the Go-Lab initiative. Although originally targeting pre-university learners, Go-Lab's virtual and remote labs have the potential to be adapted for higher education. The platform supports more than 500 laboratories and 40 tools for guided inquiry,and promotes student engagement through structured inquiry-based learning spaces (ILS). Additional Spanish studies also explore gamified platforms such as TAECon, which aim to increase student interest in STEM fields.

In **Romania**, VL use is more targeted and specialized, with a strong emphasis on inclusive education. The NEWTON project, for example, incorporates VR tools with sign language avatars and sensory feedback to support hearing-impaired students. Similarly, the EurOP2E project focuses on clinical pharmacology education and promotes collaborative creation of digital teaching materials for medical education across Europe. Although Romania's overall deployment of VLs is less widespread than in Greece or Spain, its commitment to accessibility and pedagogical inclusivity represents a key contribution to the European landscape.

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6.2. Common practices and methodologies

Several shared practices emerge across the partner countries. All countries, to varying degrees, employ inquiry-based learning (IBL) frameworks within their VL activities. Platforms such as Graasp (Cyprus), Go-Lab (Spain), and Onlabs (Greece) structure the learning experience around student-driven exploration, hypothesis testing, and reflection. This inquiry-based approach not only promotes conceptual understanding but also encourages critical thinking and scientific reasoning.

Gamification and immersive technologies, including virtual reality and decision-based scenarios, are also increasingly incorporated into VLs. Greece and Romania stand out in this regard, with applications in biomedical, psychological, and accessibility-focused education. Spain's TAECon platform similarly integrates game elements into its problem-based learning model.

Another common trend is the use of hybrid and blended learning models, combining virtual labs with physical instruction. In Romania and Greece, such approaches have demonstrated improved learning outcomes, particularly in terms of student engagement, motivation, and knowledge retention.

The studies across all countries also underscore the reliance on online platforms to host and manage VL activities. Whether through proprietary platforms like Go-Lab and TAECon or general-purpose systems such as Graasp, the digital delivery of laboratory experiences is now an integral component of pedagogical strategy in partner institutions.

6.3. Identification of common challenges

Despite promising developments, several common challenges hinder the broader adoption and effective use of VLs.

One of the most frequently cited barriers is the lack of adequate technological infrastructure. This includes limitations in access to VR equipment, high-performance computing, and stable internet connections, especially relevant for immersive environments. Romania and Greece report these issues as significant constraints on scalability.

Faculty training and digital readiness present another persistent issue across countries. Teachers and faculty often lack the necessary training to design, implement, or assess virtual learning activities effectively. Spain and Romania particularly emphasize the steep learning curve and resistance to pedagogical change among educators transitioning from traditional to technology-enhanced models.

Furthermore, all countries identify the need for standardized guidelines and evaluation tools for virtual laboratories. The absence of coherent national or institutional policies creates inconsistency in how VLs are integrated into curricula and how their impact is measured.

From a pedagogical standpoint, challenges related to student autonomy and motivation are noted in Spain and Cyprus. Inquiry-based learning demands a high degree of independence from learners, which may not align with students' previous educational experiences.

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Inclusion and accessibility, while emphasized in Romania, remain under-addressed in the other countries. Studies from Cyprus, Greece, and Spain rarely consider learners with disabilities, gender-based inclusion, or other factors related to equitable learning environments. This reflects a broader need to embed Universal Design for Learning (UDL) principles into the development of VL content and platforms.

6.4. Good practices and transferable models

Several successful practices and models have emerged that are suitable for transfer or adaptation across countries.

The Go-Lab project in Spain is a model of scalable, multilingual, and accessible VL implementation. Its suite of over 500 online labs and flexible inquiry-based framework (ILS) offers a replicable structure that can be customized to local educational contexts, including higher education.

In Greece, the use of Onlabs for biology education and other VR applications for biomedical training demonstrate effective integration of virtual tools into existing curricula. These practices highlight how VLs can enhance not just conceptual learning but also practical skills and professional preparedness.

Romania’s NEWTON project is particularly noteworthy for its inclusion of students with hearing impairments. Its use of sign language avatars and gamified content addresses a critical gap in inclusive STEM education. Similarly, the EurOP2E project provides a collaborative framework for co-developing problem-based VL content in medical education, demonstrating the value of cross-border academic cooperation.

From Cyprus, while the scale of implementation is limited, the country provides a robust example of policy foresight and strategic planning through its studies on institutional readiness for integrating emerging technologies.

6.5. Shared needs and policy implications

Across all participating countries, several shared needs have been identified that could inform future EU-level policy and funding mechanisms.

First, there is a strong consensus on the need for standardized guidelines that define quality benchmarks for virtual laboratory design, implementation, and evaluation. Such guidelines would help ensure consistency and interoperability across institutions and countries.

Secondly, there is an urgent need for ongoing faculty development and training programmes. Given the evolving nature of educational technologies, short-term workshops are insufficient. Instead, sustainable and scalable training infrastructure is required to build long-term capacity within higher education institutions.

Investment in technological infrastructure remains a priority. Countries with limited access to VR/AR equipment or poor connectivity are at a disadvantage, especially as immersive technologies become more central to laboratory-based education.

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Another critical area is the integration of inclusive design principles. Romania provides a strong example of this through the NEWTON project, but similar considerations need to be mainstreamed in all VL initiatives to ensure equitable access for all learners.

Lastly, there is a shared call for better curriculum integration frameworks. VLs are most effective when not treated as supplementary or experimental tools but rather embedded within the core instructional design of university programmes.

7. Overall findings from the implementation of VHEalthLab

This section presents the main findings for each country based on the quantitative and qualitative results of the VHEalthLab implementation. Across Cyprus, Greece, Romania, and Spain, implementations involved higher-education lecturers, secondary-school teachers, and pre-service teachers. Delivery modes varied (on-site, online, or blended), but all participants engaged with Training Module 1, the Pedagogical Guidelines, and at least one of the four virtual labs: Lab Safety, Light Microscopy, Cell Structure and Function, Cell Division. This diversity of roles and settings strengthens the external validity of results and surfaces, practical constraints relevant to scale-up.

Cyprus

The analysis of pre- and post-questionnaires showed a marked increase in educators' confidence with virtual labs: while only two-thirds initially felt confident, all post-survey participants agreed on ease of navigation, clarity of instructions, and task completion, confirming the training's effectiveness. At the same time, areas for refinement emerged around assessment design, navigation tools, and instructional clarity. Qualitative feedback reinforced these results, with participants valuing the clear step-by-step structure, authentic multimedia, and strong pedagogical support, particularly in clarifying complex concepts and preparing students for hands-on labs. However, improvements were urged in accessibility (larger fonts, captions, voice-overs), formative feedback, and differentiated tracks for secondary and higher education. Overall, the findings affirm the platform's educational value and usability, while offering targeted recommendations to strengthen its classroom integration and policy relevance.

Greece

Combined quantitative and qualitative findings from the implementation at the Aristotle University of Thessaloniki (AUTH) highlights that tutors of Higher Education were genuinely interested and impressed by the potential of VLs to enhance the learning process of students ensuring at the same time better knowledge acquisition and

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engagement in learning. Insights from interviews and the focus group underscored the value of VLs for Higher Education promoting students' engagement and in depth interaction with the content explored in the Biology Labs. VLs were considered significant tools that should be incorporated into the curriculum with the aim to enhance the introduction of concepts, provide checkpoints for understanding and even be used as homework activities in the context of flipped learning. As a whole, VHEalthLab demonstrates substantial usability and pedagogical promise. Its highest strengths are usability, accessibility and the ability to put inquiry-based practices into a range of learning situations. To position itself as a truly useful addition to laboratory teaching, future development should focus on making the virtual labs more interactive, accessible and rich in content so that they are not merely convenient to use but also intellectually stimulating to various types of learning requirements.

Romania

The implementation of the VHEalthLab pedagogical framework in Romania offers compelling evidence that well-structured digital resources can significantly advance STEM education. Both quantitative and qualitative results affirm the pedagogical viability and instructional value of virtual laboratories when coupled with practical guidance and aligned with classroom realities.

The report highlights a key shift: educators are no longer questioning whether to integrate digital tools, but rather how to do so in ways that are inclusive, curriculum-responsive, and pedagogically sound. This transformation is not merely technological; it is profoundly pedagogical. The findings position VHEalthLab as a forward-thinking model for how digital learning environments can foster inquiry, equity, and active learning in science education.

Moreover, these results speak directly to European policy efforts aimed at modernizing teacher education and digital competence. By showcasing scalable strategies for adoption, the report (Appendices) contributes to a broader vision of resilient, inclusive, and digitally enriched education systems. This is not just an assessment of a single intervention: it is a roadmap for integrating technology meaningfully into the evolving landscape of science teaching and learning.

Spain

Combined quantitative and qualitative findings from the implementation at the University of Santiago de Compostela demonstrate that VHealthLab materials significantly boosted pre-service faculty confidence, usability perceptions, and readiness to adopt virtual labs in STEM education. Initially, varied digital skills and limited hands-on experience gave way to uniformly positive post-training evaluations of platform navigation, instructional clarity, and inquiry-based pedagogy. Insights from interviews and the focus group underscored the value of case contextualization,

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audiovisual material, practical examples, and inclusive guidelines, while identifying priorities for greater interactivity, more formative assessment, and improved accessibility. Together, these insights validate VHealthLab's intuitive design and pedagogical approach and provide clear direction for materials refinement. By addressing the highlighted improvements, the project can further empower future teachers to effectively integrate virtual labs, fostering active and inclusive science learning.

Across contexts, educators reported high usability, strong alignment with inquiry-based learning, and tangible support for inclusion. At the same time, recurring needs emerged around interactivity, formative feedback, navigation consistency, and curricular alignment.

8. Conclusions

This comparative analysis provides a comprehensive overview of the current use of VLs within STEM and health education across the four participating countries, namely Cyprus, Greece, Spain, and Romania. The findings reflect a diverse landscape in terms of technological maturity, pedagogical integration, and institutional readiness.

In Greece, VLs are well integrated at the university level and applied across various scientific disciplines through established platforms and structured educational approaches. Spain demonstrates wide-scale implementation, particularly in secondary education through initiatives such as Go Lab (Sierra et al., 2020), which shows strong potential for adaptation to higher education settings. Romania presents a focused approach, with VLs supporting inclusive education using virtual reality environments designed for learners with special educational needs (Bratu et al., 2023). Cyprus is in an emerging phase, where institutional interest is growing, supported by pilot studies and initial readiness assessments (Nisiforou et al., 2024).

Despite differences in national contexts, several common challenges were identified. These include limitations in technological infrastructure, restricted access to immersive and digital tools, insufficient training and digital preparedness among academic staff, and the absence of standardised frameworks for integration into curricula and assessment practices. Addressing these barriers is essential to support the effective and sustainable use of virtual laboratories within higher education systems.

At the same time, the evidence reviewed clearly confirms the pedagogical value of VLs. Virtual laboratories contribute meaningfully to experimental science education by enhancing student engagement, supporting inquiry-based learning, and improving conceptual understanding. They also provide flexible and scalable solutions for accessing laboratory experiences in situations where traditional facilities are unavailable, impractical, or resource constrained. Moreover, their adaptability

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contributes to the promotion of inclusive learning environments by enabling participation across a wider spectrum of learners, including those in remote or underserved settings.

The integration of the research and practical phases was deliberate: the VL design (Papalazarou et al., 2024; Ewais et al., 2024) was directly informed by the literature review, which provided a blueprint for pedagogical effectiveness and addressed national challenges. Specifically, the Greek experience with structured simulations (Paxinou et al., 2020) and the Spanish emphasis on Inquiry-Based Learning (IBL) (Sierra et al., 2020) provided models for the instructional design framework adopted. Furthermore, the Romanian focus on VLs for inclusive education (Bratu et al., 2023) underscored the need to ensure the VL could accommodate diverse learners, particularly when addressing the general digital readiness issues noted in the literature. Subsequently, the **implementation and evaluation phase** (Nisiforou et al., 2024; Tsivitanidou et al., 2021) expanded the conclusions by providing concrete evidence regarding **institutional preparedness** (Nisiforou et al., 2024) and validating the challenges around infrastructure and faculty training identified broadly in the literature. The implementation also yielded new, nuanced data on the interaction between **VL learning gains and specific student attitudinal profiles** (Tsivitanidou et al., 2021), adding depth to the general findings on student impact reported in the initial review.

Virtual laboratories represent a critical and evolving component of digital education in Europe. To support their meaningful and coherent integration, there is a clear need for strategic coordination and policy development across European countries and institutions.

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Appendices

Cyprus implementation report here

Greece implementation report here

Romania implementation report here

Spain implementation report here

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