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

WP5 Task 5.6

POLICY REPORT

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Executive Summary

VHEalthLab is an open online platform that combines Virtual Laboratories with a pedagogical toolkit to enable high quality practical science learning in safe, scalable, and inclusive ways. It addresses long standing constraints of physical laboratories, including cost, safety, access, and capacity, while responding to the post pandemic demand for flexible and blended provision. The platform strengthens digital readiness, supports inquiry-based teaching, and contributes to more resilient, equitable, and future oriented STEM education across Europe. This report presents the Virtual Laboratories, the open access online course with pedagogical guidelines, and early implementation evidence from Spain, Cyprus, Greece, and Romania, including testimonies from higher education educators and preservice teachers. It is intended to familiarise policy makers with the VHEalthLab resources and to support their curricular adoption within secondary and higher education systems, in alignment with European priorities for digital transformation and inclusive learning.

Purpose of the Report

The purpose of this report is to introduce the Virtual Laboratories and associated pedagogical toolkit developed through the VHEalthLab project, to present early implementation insights from partner countries, and to inform national and European policy makers of the opportunities for curricular adoption. The report aims to support the integration of Virtual Laboratories within STEM and health education by demonstrating their pedagogical value, practical feasibility, and contribution to equity, digital competence development, and innovation in higher education.

Key Findings

Evidence gathered across partner countries shows that Virtual Laboratories offer strong educational value and are aligned with European objectives for modernising higher education, strengthening digital capabilities, and widening participation in STEM. The findings confirm that inclusivity is embedded through multilingual access, support for diverse learning needs, and attention to gender balance. At the same time, implementation remains uneven due to disparities in technological infrastructure, gaps in educator preparedness, and the absence of standardised guidelines and evaluation frameworks. These challenges highlight the need for coordinated action to ensure that Virtual Laboratories can be adopted consistently and equitably across Europe.

Main Policy Recommendations

The report proposes a set of policy recommendations designed to enable effective scale up and institutionalisation of Virtual Laboratories. These include the development of standardised guidelines and evaluation frameworks, the

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establishment of regional Teacher Academies to provide sustained professional development, the prioritisation of funding for technological infrastructure and accessible multilingual VL content, the promotion of cross border collaboration and open resource sharing, and the embedding of VHEalthLab within national STEM and digital education strategies. Together, these actions will support quality assurance, teacher capacity, institutional readiness, and sustainable system wide adoption.

Forward Looking Statement

Implementing these recommendations will allow European countries to expand access to high quality laboratory learning, strengthen the alignment between education and labour market needs, and contribute to a digitally skilled and innovation driven workforce. VHEalthLab offers a ready to deploy solution that supports inclusive, resilient, and future ready science education, positioning Europe to lead globally in the advancement of digital learning practices and equitable STEM participation.

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1. Rationale and Context

Education systems worldwide continue to move toward open and distance provision, a transition accelerated by the pandemic, which normalised blended learning as a technology enhanced approach combining classroom and online modes. Virtual environments now play a major role in developing the technical and transversal skills essential for lifelong learning, including problem solving, critical thinking, collaboration, creativity, and digital literacy.

STEM education is a primary pathway for these skills because it emphasises hands-on learning with real world applications. Yet Europe faces a declining interest in STEM careers among young people, creating both educational and economic challenges. International and European policy frameworks identify STEM competence as essential for preparing the future workforce.

Science education also faces a practical challenge in providing laboratory experience when physical facilities are inaccessible, limited, or resource intensive. Virtual Laboratories offer authentic practice opportunities that enable students to carry out experiments and achieve target learning outcomes. They now complement face to face instruction across STEM domains.

Evidence from Cyprus, Greece, Spain, and Romania shows that Virtual Laboratories exist but are unevenly embedded in higher education. Cyprus demonstrates feasibility but needs stronger curricular alignment. Greece reports learning gains but faces infrastructure and faculty development constraints. Spain shows significant secondary school uptake but limited higher education adoption. Romania highlights inclusion focused applications but reports resource and standardisation challenges.

These findings demonstrate a clear policy need for coordinated action including: inquiry based Virtual Laboratories embedded in curricula, shared quality and evaluation guidelines, sustained professional development for educators, reliable connectivity and infrastructure, and universal design and multilingual access. VHEalthLab responds directly to these needs by offering open access Virtual Laboratories in biology, implementation guidance, assessment support, educator training, and multilingual resources. As such, it aligns with European priorities for

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digital transformation, inclusive higher education, and preparation for green and digital transitions.

2. VHEalthLab Project Objectives

2.1. Overall Objective

Promote the curricular adoption of VHEalthLab and the open online course with pedagogical guidelines among National and European policymakers to enhance quality, equity and efficiency in STEM education.

2.2. Specific Objectives

- **a.** Raise awareness of the VLs and the open-access online course among policy makers and curriculum agencies in partner countries.
- **b.** Inform policy makers and curriculum agencies in partner countries about the VHEalthLab platform.
- **c.** Evidence the pedagogical and organisational benefits of VLs (inquiry-based learning, motivation, digital competences, safety/cost-efficiency).
- **d.** Provide a pedagogical framework for the application of VHEalthLab across countries (usage scenarios, teacher training, integration into modules and courses).
- **e.** Introduce inclusion policies (gender gap and diverse learning needs) through guidelines and Training modules for the implementation of VHEalthLab.
- **f.** Propose actions for national and institutional scale-up (e.g., pilot programmes, recognition/credit for the open course, technical-pedagogical support, monitoring and evaluation) that align with EU priorities on digital transformation and STEM education.

3. VHEalthLab platform

Project Website: www.vhealthlab.eu
VHEalthLab platform: https://vhealthlab.elearning.ro

This section summarizes the materials and educational aspects covered by the VHEalthLab platform, as well as what this platform offers to secondary and higher science educators, teachers, and policymakers. Practical information about the characteristics, functionalities and main components of the VHEalthLab platform is presented below.

- **Open-access platform**: VHEalthLab platform is an open online environment for secondary and higher education learners, and for initial teacher education.

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- **Languages**: English, Spanish, Greek and Romanian.
- **Pedagogical approach**: Inquiry-based learning with guided pathways, scaffolding and feedback for all VHEalthLab cases is provided.
- **Inclusion**: The platform integrates materials and guidance addressing gender equity and diverse learning needs.
- **Usability**: The platform provides step-by-step navigation, short tasks and clear objectives to reduce cognitive load and support self-regulation.
- **Educators support:** Training modules and a pedagogical guide designed for lecturers and pre-service teachers, with guidance on classroom implementation and adaptation for three usage scenarios (group, individual and remote) are provided.

3.1. Virtual labs

VHEalthLab offers a coherent suite of fourteen VL activities that span core domains of General Biology and Health Sciences, while modelling an inquiry-based learning (IBL) approach. Each VL activity follows a consistent structure including clear learning objectives, a guided investigation pathway, embedded checks for understanding, and prompts for interpretation and communication of results, allowing teachers to deploy them in group, individual, or remote scenarios. Collectively, the VLs progress from foundational techniques (light microscopy, lab safety, use of basic equipment) to discipline-specific practices (cell division, electron microscopy, restriction digestion, DNA isolation/PCR, microbial culture), and finally to integrative reasoning (biomolecules, enzymology, probabilities/biostatistics, cell culture).

Objectives are written at multiple cognitive levels (identify/describe, apply/interpret, analyse/evaluate/design) to support curriculum alignment and assessment. All materials are available in English, Spanish, Greek, and Romanian, with inclusive design features that reduce cognitive load and promote equitable participation. The overview below summarises each virtual lab alongside its targeted learning outcomes.

Table 1. Virtual lab activities included in VHEalthLab Platform.

VL Activity	Learning objectives

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1. Light Microscopy	1. Identify the principal parts of the compound microscope and their practical utility. 2. Identify the steps necessary to properly observe a microscopic organism. 3. Explain the procedure for preparing a wet mount to observe it properly. 4. Identify and solve potential problems when preparing and observing wet mounts under the microscope.
2. Cell Division I (Mitosis)	1. Describe the process of mitosis and its stages. 2. Explain the significance of mitosis in cell division and organismal growth. 3. Identify the stages of mitosis in prepared slides of mitotic cells. 4. Relate the process of mitosis to real-world examples, such as tissue regeneration or growth.
3. Cell Structure and Function	1. Explain the process of osmosis in onion root cells and red blood cells. Define Osmosis. 2. Identify the importance of selective permeability and explain its role in Osmosis. 3. Differentiate the terms hypotonic, isotonic, hypertonic solution with respect to the concentration of osmotically active substances. 4. Predict and evaluate the impact of different solutions on plant and animal cells using the appropriate terminology.

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4. DNA Isolation and PCR	1. Explain the process of isolation for genomic DNA from a tissue sample and its potential applications. 2. Explain the principles and process of a PCR, using genotyping of transgenic mice as an example. 3. Analyze and interpret the results of a PCR experiment with gel electrophoresis, using as an example the genotyping of transgenic mice. 4. Identify and explain the most common causes of failure in a PCR experiment.
5. Biomolecules	1. Interpret tests for detecting carbohydrates, including reducing sugars and starch. 2. Identify the presence of lipids by using specific testance of mitosis in cell division and organismal growth. 3. Describe the presence of proteins based on the interpretation of a test. 4. Determine the presence of DNA using specific tests. 5. Relate the presence of certain biomolecules in the urine to health disorders.
6. Metabolism of Cell Enzymes (temperature and pH)	1. Distinguish the terms substrate, active site and product in the context of enzymatic activity. 2. Explain the main factors that affect enzymatic activity. 3. Describe the experimental steps to identify an enzyme's optimal pH and temperature, using amylase as an example. 4. Interpret the results to identify the optimal temperature and pH for enzyme activity, using amylase as an example.

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7. Lab Safety	1. Identify and explain at least five necessary safety measures for a biology laboratory. 2. Demonstrate the correct application of good laboratory practices. 3. Select and justify the use of appropriate personal protective equipment (PPE) for various laboratory scenarios. 4. Recognize and interpret at least six common chemical hazard symbols. 5. Outline the structure of a scientific lab report, identifying all required sections and their purposes.
8. Electron Microscopy	1. Describe the basic functioning of an electron microscopy. 2. Explain the scientific rationale for using electron microscopy in investigating subcellular changes in tumor models. 3. Compare the basic elements and uses of light and electron microscopes, linking these differences to their suitability for studying biological samples. 4. Identify the core components of an electron microscope and explain how it contributes to image generation. 5. Differentiate between Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) and prioritize their applications based on research objectives.
9. Restriction Endonuclease digestion	1. Explain the principles and steps of restriction endonuclease digestion of DNA. 2. Identify the applications of restriction endonuclease digestion of DNA. 3. Analyze and interpret the results from gel electrophoresis resulting from restriction endonuclease DNA digestion.

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10. Mendelian Genetics and Genetic Problems	1. Define the term Genetics. 2. Differentiate between key genetic concepts, [including alleles, genotype, phenotype, dominance, recessiveness, homozygosity, heterozygosity, carrier] by analyzing inheritance pattern. 3. Apply Mendel's law to predict trait inheritance using Punnett squares for monohybrid crosses. 4. Interpret Punnett squares to determine the probabilities of genetic disease like Thalassemia. 5. Apply Mendelian inheritance to real-world genetics diseases.
11. Microbial culture and growth	1. Apply laboratory safety principles and aseptic technique in handling microorganisms. 2. Explain the utility of differential and selective media to profile bacterial growth. 3. Describe how to quantify microbial presence in biological samples. 4. Identify the key steps and principles of isolating and culturing pure bacterial strains for identification.
12. Using basic lab equipment (pipettes, scales, centrifuge, spectrophotometer)	1. Identify and describe the function of basic laboratory equipment. 2. Explain the correct usage techniques for pipettes and scales. 3. Describe the function of a centrifuge and spectrophotometer safely and effectively. 4. Apply good laboratory practices to ensure precision and reliability when handling basic laboratory equipment 5. Identify common errors when using laboratory equipment and propose corrective actions to improve technique and data quality.

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13. Biostatistics: Introduction to probabilities	1. Describe how karyotyping detects chromosomal abnormalities and its role in identifying phenotypic traits. 2. Understand and apply the multiplication rule and addition rule in predicting genetic inheritance patterns. 3. Apply the binomial rule to predict probabilities of different genotypes across multiple offspring. 4. Evaluate the role of probability in explaining Mendelian and chromosomal inheritance into clinical or research settings.
14. Cell Culture	1. Identify the essential components and environmental conditions required for mammalian cell culture 2. Describe proper aseptic techniques to minimize contamination and ensure successful cell growth in laboratory experiments. 3. Interpret experimental data to assess the dose-dependent effects of Supplement X on HeLa cell survival and behavior. 4. Evaluate the potential implications of Supplement X treatment on cancer cell survival and therapeutic strategies. 4. Design a basic experimental setup with appropriate controls to test and compare multiple treatment conditions.

3.2. VHEalthLab Pedagogical Framework

VHEalthLab is grounded in Inquiry-Based Learning (IBL) in science education. According to this approach, learners construct scientific knowledge by asking questions, formulating hypotheses, investigating phenomena, analyzing evidence, and communicating conclusions. The framework prioritizes the development of scientific reasoning, problem-solving, and evidence-based argumentation and decision-making, competencies that align with contemporary European priorities for digital transformation, critical thinking and creativity.

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The inquiry cycle used in VHEalthLab follows five flexible phases: Engage, Problem Definition, Investigation, Conclusion, and Discussion. Learning scenarios begin with real-world prompts that spark curiosity, then guide students to design or follow investigations, interpret findings, and reflect on constraints, challenges and implications. Crucially, the cycle is iterative rather than linear: learners may revisit earlier steps as new insights emerge, mirroring authentic scientific practices.

Teacher practice and instruction are crucial. VHEalthLab positions educators as facilitators, instructors, and mentors who calibrate scaffolding (targeted supports that fade as competence develops) and guidance (the level of learner autonomy) across four inquiry levels: verification, structured, guided, and open. This calibration enables safe and purposeful exploration in virtual labs while maintaining alignment with curricular goals and assessment standards.

Assessment addresses both the learning process and its outcomes. In addition to content knowledge, teachers evaluate inquiry practice, such as the quality of questions and hypotheses, appropriateness of methods, rigor of data analysis, and clarity of arguments, through reports, presentations, portfolios, discussion forums, and built-in activity quizzes.

The framework is delivery-agnostic and supports multiple implementations: group collaboration, self-paced individual work, and remote/asynchronous use, so institutions can adapt to timetable, infrastructure, and cohort needs. Across settings, the design encourages metacognition (learning journals, reflection prompts) and real-world transfer (challenge-based tasks and application discussions).

Finally, VHEalthLab embeds practical preparation for hands-on laboratories: virtual experiences introduce procedures, equipment, and safety, reducing errors and increasing efficiency when students transition to physical labs. This coherent, evidence-based pedagogy ensures that the platform is not merely a digital repository but a structured environment for cultivating inquiry, resilience, and scientifically literate graduates.

3.3. Inclusion. Gender Gap and Learning Needs

VHEalthLab treats inclusion as a design principle, not an add-on. It is addressed along two complementary dimensions. First, the gender gap in STEM: under-representation and lower persistence of women linked to stereotypes, uneven participation, and confidence gaps. Second, diverse learning needs: differences in processing speed, prior knowledge, language proficiency, attention, and preferred modalities that shape how students access, engage with, and demonstrate learning.

The platform addresses these priorities indirectly through the VLs activities. Each activity uses clear, stepwise pathways with concise text and visual supports, allowing students to proceed at their own pace and revisit steps as needed. Multilingual availability (English, Spanish, Greek, Romanian) reduces language barriers for

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non-native speakers. Narratives and example dialogues are written to avoid gender stereotyping and to normalise balanced participation in decision-making and problem-solving across group, individual, and remote scenarios. This design lowers cognitive load, supports confidence building, and widens access without singling out particular groups.

In parallel, inclusion is directly operationalised in the pedagogical guide and the training modules, which offer concrete strategies for teachers. For gender equity, the materials recommend rotating roles in group work (equipment handling, data analysis, presentation) so all students, especially girls, lead hands-on tasks and contribute to key decisions; using equitable questioning and feedback (balanced turn-taking, scaffolded support for complex questions); integrating female role models and case studies; and applying bias-aware assessment that values inquiry processes as well as products. For diverse learning needs, the guidance includes planning checklists for multimodal resources (text/audio/video), chunking complex tasks with formative checkpoints, allowing flexible timing, providing language supports (glossaries, simplified prompts), and accepting multiple output formats (explanations, concept maps, short presentations) so students can evidence understanding through different strengths.

Taken together, this dual approach, inclusive-by-design activities complemented by actionable teacher guidance, promotes equitable access, meaningful participation, and fair assessment. It provides institutions with a practical, scalable model aligned with EU priorities for inclusive digital education and for widening participation in STEM.

3.4. Inquiry-based Pedagogical guidelines

The Pedagogical Guidelines set out how VHEalthLab's virtual laboratories are implemented through an inquiry-based learning approach (IBL) in secondary and higher education. The guide defines the inquiry cycle: Engage, Problem Definition, Investigation, Conclusion, and Discussion, as an iterative process in which students ask questions, formulate hypotheses, gather and analyse evidence, and communicate reasoned conclusions. It clarifies the roles of scaffolding and guidance, showing how targeted supports can fade as competence grows and how autonomy can be calibrated across verification, structured, guided, and open inquiry.

Teacher practice is central throughout. The guide positions educators as facilitators, resource providers, instructors, mentors, and assessors, and offers practical strategies for modelling inquiry, posing effective questions, and giving formative feedback that strengthens scientific reasoning and metacognition. Assessment is framed to value both process and product, combining reports, presentations, portfolios, concept maps, and experimental proposals with embedded checks for understanding and activity-specific quizzes.

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Inclusion is addressed explicitly. The guide outlines measures to reduce the gender gap: balanced participation, rotating group roles, bias-aware questioning and assessment, and the use of female role models; and to support diverse learning needs through multimodal resources, chunked tasks, self-paced progression, language supports and multiple formats for demonstrating learning. These recommendations are aligned with platform features such as multilingual availability, stepwise pathways and gender-inclusive narratives.

Implementation guidance is provided for three delivery modes: group work, individual self-paced learning, and remote/asynchronous use. Each type includes before/during/after suggestions (question formulation, evidence analysis, reflection and debate) to maintain an inquiry orientation across contexts. Finally, the guide recommends using the virtual labs as preparation for hands-on sessions, introducing procedures, equipment and safety in advance to reduce errors and improve efficiency when students move to physical laboratories. Overall, the Guidelines translate an evidence-based pedagogy into concrete classroom practices that institutions can adopt at scale.

3.5. Training modules

Training module 1: Introduction to VHEalthLab and IBL.

This module introduces VHEalthLab and outlines the benefits and limitations of VLs, then anchors implementation in an Inquiry-Based Learning framework. Teachers are guided through the inquiry cycle with concrete VHEalthLab examples, and are supported to adopt multiple roles (facilitator, mentor/guide, etc.). The module provides examples of guidance vs. scaffolding, offering practical strategies to engage students in inquiry-based learning from less structured to more structured teachers' guidance. Finally, it presents three classroom **implementation scenarios** (group work, individual/self-paced, and remote use), each with inquiry opportunities, teacher actions, and inclusion considerations, highlighting multilingual access and design choices that help reduce gender and accessibility gaps. The module closes with an interactive planning task so educators can adapt a chosen VHEalthLab case to their context.

Training module 2: Pedagogical strategies for implementing VLs with the IBL approach.

This module turns the IBL framework into classroom practice for VHEalthLab. It gives teachers concrete strategies to design, run, and assess inquiry across pre-, during-, and post-lab phases. It begins by revisiting IBL's essentials: question-driven learning, staged inquiry, scientific skills, active student roles, and then tackles practical teacher challenges with targeted, ready-to-apply advice.

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Teachers are guided to craft IBL situations in seven steps: setting objectives; launching a real-world scenario to spark curiosity; structuring guided exploration in the virtual lab; using evidence for analysis and conclusions; facilitating communication and debate; assessing both process and outcomes; and connecting learning to authentic applications. This is illustrated with short examples (e.g., Cell Division, Enzyme Metabolism) and ready-to-use prompts. Inclusion is embedded via equitable roles, gender-inclusive examples, flexible formats, and adaptations for diverse learning needs. The module also provides indicators to recognise whether students are applying inquiry, in order to help teachers recognise and adjust their teaching practice in real time. It closes with a brief planning task so teachers can adapt a chosen VHEalthLab activity to their context immediately.

Training module 3: Addressing diverse learning needs and gender gap in VHEalthLab.

This module translates the pedagogical guidance on inclusion into practical classroom action. It clarifies what inclusive science education entails and why it matters for inquiry-based virtual labs, then focuses on two fronts: (1) understanding and reducing the gender gap in STEM, and (2) identifying and supporting diverse learning needs. Teachers get concrete strategies to counter bias in group dynamics and evaluation.

Regarding student learning diversity, the module helps teachers identify needs in processing speed, learning preferences, attention, pace/autonomy, language, and digital confidence, and how to address them with practical examples. It then shows how to embed these practices into the three implementation scenarios: group work, self-paced use, and remote learning; using VHEalthLab features to personalize inquiry without sacrificing rigor. An applied case and an “interactive task” guide teachers to design an inclusive, IBL-aligned VHEalthLab session tailored to their class context.

4. VHEalthLab Implementation

4.1. Methodology

4.1.1. Data collection and research instruments

This section reports quantitative and qualitative data on the implementation of VHEalthLab across the partner countries. The evaluation covered three components: Module 1: Introduction to Virtual Labs and 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. Implementation featured country-specific particularities which are described in the country results below.

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4.1.2. 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.

4.1.3. Qualitative data: Interviews and Focus group

The qualitative data were gathered through a series of written/oral interviews, as well as focus group sessions, 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 discussion. This combined approach ensured a comprehensive understanding of users' experiences and needs.

4.1.4. Methods for data analysis: Interviews and focus group

Qualitative data from both interviews and the focus group were analyzed using discourse analysis approaches, drawing specifically on content analysis techniques. Following Braun and Clarke's six-step thematic framework, written responses and oral contributions were coded and progressively refined, moving from an initial set of 24 codes to five overarching themes that captured the core insights emerging from participants.

For the interviews, the analysis revealed recurring perspectives clustered around key areas of user experience and pedagogical relevance. Participants frequently reflected on navigation and interface usability, commenting on how the platform facilitated, or at times complicated, their interaction with digital materials. They also discussed the quality of multimedia resources, the structure and clarity of assessments and feedback, and the perceived pedagogical value of the virtual labs in supporting learning. Considerations regarding curricular alignment and practical constraints affecting implementation also emerged, alongside a variety of additional remarks that extended beyond the main thematic categories.

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The focus group findings echoed several of these themes, with participants similarly emphasizing usability, multimedia quality, assessment mechanisms, and the educational role of virtual labs. However, the group setting allowed for more detailed discussion of lab-specific aspects, where participants offered both positive reflections and constructive suggestions for improvement. The conversation further extended into feedback on pedagogical guidelines and the first instructional module, again balancing affirmations with identified areas for enhancement. As in the interviews, participants also shared additional observations that fell outside the main themes but contributed valuable contextual nuance.

4.1.5 Iterative Refinement and Response to Participant Feedback

A central component of the VHEalthLab implementation methodology was a commitment to iterative improvement based on direct user feedback. The data collected from questionnaires, interviews, and focus groups was not only used for evaluation but also served as an immediate input for refining the platform and its pedagogical resources. The project team established a systematic process to review, prioritize, and act upon the concerns and suggestions raised by participants. This process involved consolidating the thematic analysis of feedback from all partner countries to identify recurrent challenges and enhancement priorities.

4.2. Results by country

This section presents the main findings for each country based on the quantitative and qualitative results of the VHEalthLab implementation. It summarises participant profiles, implementation contexts, and the key themes emerging from the data. The Transnational Report, available here, provides detailed and disaggregated analyses that inform the findings presented in this section.

4.2.1. *Cyprus*

Context, participants and data collection

The Cyprus implementation was conducted online by the University of Nicosia (UNIC). The participant cohort reflected a wide range of educational backgrounds and teaching experiences. The focus group and interview participants included experienced secondary biology teachers, university lecturers in biology education, and pre-service teachers engaged in practical training. All had completed the teacher-guidance module and at least two of the virtual labs prior to participating.

The participants worked in public and private institutions across Cyprus, contributing perspectives from both urban and rural educational settings. This diversity enabled a nuanced analysis of the platform's adaptability to various classroom conditions.

Quantitative data: Key findings

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The questionnaire respondents overlapped partially with the qualitative sample but also included new contributors. Altogether, 18 educators completed the pre-questionnaire online, and 17 completed the post-questionnaire.

The quantitative analysis of pre- and post-questionnaires showed a clear increase in educators' confidence and competence in using virtual labs. While the pre-questionnaire revealed mixed levels of prior experience and digital readiness, with only two-thirds initially confident, the post-questionnaire results demonstrated unanimous agreement on ease of navigation, task completion, and clarity of instructions. This strong consistency contrasted with earlier variability and confirmed the effectiveness of the training in building digital teaching capacity. The data also identified specific areas for improvement, including assessment design, navigation features, and clearer instructional support. Overall, the findings highlight the training's success in enhancing educator preparedness while generating practical recommendations for refining virtual lab implementation.

Qualitative data: Key findings

A 105-minute focus group was conducted online with eight educators, including higher education lecturers, secondary-school biology teachers, and pre-service teachers. The conversation explored the navigation, accessibility, and instructional design of the VHEalthLab platform and elicited suggestions for improvement. The session was recorded, transcribed, and analysed with Braun and Clarke's six-step thematic framework, reducing 24 initial codes to five themes.

Following this, three follow-up interviews were conducted with selected focus-group participants to probe emerging themes more deeply and assess thematic saturation. Each semi-structured interview lasted approximately 30–40 minutes.

Qualitative data: Key findings
Shared Strengths

- Intuitive, step-by-step flow: The case-study structure guided novices through complex procedures without feeling overwhelming.

- Authentic media and decision points: Short videos, still images, and scenario-based choices sustained attention and prompted critical thinking.

- Ready-to-use pedagogy: The Pedagogical Guide was seen as directly applicable. The automatic certificate issued at the end of each lab was

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perceived as a motivating reward, and the ready-made storylines, questions, and visual assets were credited with reducing lesson-planning time for teachers.

Common Challenges

- Navigation frictions: Navigation issues dominated the negative feedback. Hidden controls such as a “plus” button that sits below the fold, and the absence of a one-click “previous step” function slowed progress, particularly in the Light-Microscopy lab.

- Accessibility limits: Small fonts/images and silent videos without labels hampered readability and support for learners with specific needs (e.g., dyslexia).

- Assessment design: Quizzes concentrated at the end, learners cannot retry incorrect answers, and the system offers no explanation of why a response is wrong. Numeric scores, interviewees argued, distract students from reflection. Finally, teachers emphasised timetable pressures forty-five-minute periods with classes of twenty to twenty-five and urged careful alignment of virtual content with the national syllabus.

Enhancement Priorities

- Accessibility and clarity: Enlarge fonts/icons/key images; add clearer on-screen labels and optional voice-overs with local-language captions; include additional diagrams where helpful.

- Formative assessment: Embed low-stakes questions after major steps, allow multiple attempts, and provide immediate explanatory feedback; add a brief post-lab learner survey.

- Navigation and differentiation: While richer media virtual-reality views or AI-assisted help were welcomed in principle, participants stressed that any new feature must rely on free, open-access tools to keep the platform universally available.

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4.2.2. Greece

Context, participants and data collection
The Greek implementation was conducted by the Aristotle University of Thessaloniki (AUTH) with participants drawn primarily from higher Education: tutors from the Department of Biology and one secondary-school biology teacher.

Quantitative data: Key findings

A total of seven (7) participants completed both the pre-questionnaire and the post-questionnaire. Five of them were tutors in higher Education at the Department of Biology of the Aristotle University of Thessaloniki, while one was a secondary education biology teacher.

The interaction with and assessment of Training module 1 took place online on September 2, 2025. This initial session aimed to provide a comprehensive overview, ensuring participants are familiar with the virtual environment and understand the learning objectives and assessment methods of the module. The session began with a brief presentation of the concept and aim of the VHEalthLab project. Following that, Virtual Labs (VLs) were introduced to participants covering several key aspects: the goals and benefits of the VLs, including how virtual laboratories can support learning and provide experience with processes that would be difficult or costly to perform in a physical lab; the structure and content of Training Module 1, outlining what participants are expected to learn and how their progress will be assessed; the ways participants can interact with the VLs, as well as the evaluation and feedback process.

As a next step, participants were asked to complete the pre-questionnaire sharing the google form. They were then given time to interact independently with the learning content, while AUTH partners remained available to provide any necessary assistance or guidance. Once this interaction concluded, participants were asked to complete the post-questionnaire.

Pre and post evaluation's results based on participants' experience with the training materials of the VHEalthLab project generally varied. Participants initially expressed interest in VLs, and after interaction with them opened up to an increasingly stronger sense of self-confidence and utilized appreciation. Rather than replacing traditional labs, VLs were mainly considered necessary complements, offering flexible ways of engaging students while highlighting the need for pedagogical guidance to be effective. Professional development and prior training emerged as an essential

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facilitator, to ensure that tutors may feel ready and competent to introduce these tools effectively into their educational practice.

Post-questionnaire results reinforced these encouraging insights, with high agreement about the clarity of instructions, ease of use and worth of instructional videos and scheduled activities. Participants found the training platform intuitive, easy to follow and ideal for supporting IBL. However, some participants felt that inquiry and exploration was not fully achieved due to the pre-defined format of the content that left no space for open discovery. Suggestions focused on ensuring stronger interactivity, more substantial scientific information, richer bibliographic tools and more interactive feedback mechanisms. Overall, VHEalthLab shows strong potential through its clarity, accessibility and structured design, making it a valuable support for IBL.

Qualitative data: Key findings

A total of five (5) participants, selected from the group that had previously engaged with VHEalthLab materials took part in the interviews. All interviews were conducted remotely and in writing. Each participant was given several days to provide their feedback, following a semi-structured format that allowed for both guided responses and open-ended comments.

This structure enabled the collection of comparable data across participants, while also offering the flexibility to capture individual perspectives and experiences in depth. The choice of conducting the interviews in writing and remotely was guided by practical considerations, such as ensuring accessibility and convenience for participants located in different geographical areas, as well as by the aim of allowing them sufficient time to reflect on their answers. This format also helped minimize scheduling constraints often encountered in synchronous oral interviews.

The focus group was conducted right after the evaluation of Virtual Lab 1 and was held online. In total, seven (7) participants took part in the session. Three (3) reported teaching experience ranging from 1 to 5 years, while the others had more than 11 years of experience. All participants were actively involved in laboratory courses in biology, which ensured that they were both familiar with the subject matter and able to provide meaningful and practice-oriented feedback. This combination of early-career and more experienced tutors offered a balanced perspective on the integration of virtual labs into teaching practice.

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The session began with an explanation of the purpose and structure of the focus group, outlining the main topics of discussion and the basic guidelines to foster a respectful and productive exchange. At the start, participants responded to the guiding questions in turn, following a clockwise order. As the discussion progressed, the format became more open, allowing participants to interact more freely, while still respecting each other's contributions.

The session lasted approximately 45 minutes and was recorded, transcribed, and subsequently analysed. Conducting the focus group online facilitated participation by reducing logistical barriers and ensured that participants could engage comfortably from their own professional settings. Within the Greek higher education context, this format was particularly relevant, as it reflected the growing reliance on digital platforms for both teaching and research activities.

Shared strengths

- Clarity and structure: Materials are well-organized; instructions are clear and easy to follow.

- Navigation and usability: Interface feels intuitive and accessible across activities.

- Multimedia and alignment: Videos/images support learning objectives and sustain engagement.

- Assessment relevance: Activities are perceived as meaningful and pedagogically aligned.

- Motivation and engagement: Design supports student motivation, active participation, and teacher confidence.

- Curriculum innovation: Potential to catalyse more up-to-date, innovative practices in higher Education.

Common challenges

- Navigation consistency: Desire for more consistent patterns and controls across modules.

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- Multimedia breadth: Need for greater variety and richer, more authentic scenarios.

- Advanced instrumentation: Interest in showcasing tools/instruments not typically available in class. For example, while traditional microscopes are already sufficiently covered, introducing advanced or rare instruments would add significant value.

- Feedback specificity: Request for corrective feedback that explicitly shows the right answers.

Enhancement priorities

- Richer multimedia and scenarios: Expanding the range of multimedia materials (e.g., scenario-based videos, updated and diverse resources).
- Formative assessment: Strengthening feedback mechanisms, particularly by integrating corrective, interactive, and differentiated feedback.
- Tutor preparation: Considering including proper support and training of tutors before implementation of VIs in practice.
- Further study resources: Providing additional references for deeper study, though these should remain aligned with the course's central focus.

4.2.3. *Romania*

Context, participants and data collection

Over 60 biology educators were invited to take part in the Romanian implementation coordinated by ASCENDIA. Out of these, 31 responded positively to the request to collaborate in the project, 8 of them being teachers in higher education, the remaining 23 being secondary school teachers. They were created accounts on the LMS platform developed within the project and provided with the interactive assessment materials. After the training, six teachers provided written interview responses and three also joined an online focus group.

Quantitative data: Key findings

The pre-evaluation questionnaire was completed by 24 participants, while the post-evaluation questionnaire recorded 20 complete responses. Participants were drawn from both higher education and secondary education contexts, primarily within

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the field of biology. They participated in an online training session held on September 2, 2025, during which they were introduced to the project's objectives, its modular structure, and the pedagogical potential of the virtual laboratories.

The quantitative data revealed a marked increase in participants' digital confidence, pedagogical readiness, and willingness to integrate virtual laboratories into their teaching practice. Pre-intervention results showed a generally high level of openness to digital tools, especially when accompanied by pedagogical guidance. Post-intervention responses confirmed that exposure to the VHEalthLab platform and Module 1 significantly strengthened participants' perceptions of usability, clarity, and instructional value.

Importantly, teachers highlighted the virtual labs as effective complements to physical laboratories, rather than substitutes, and emphasized their role in promoting IBL and scientific thinking. The result analyses revealed no significant differences between experienced and novice users of digital tools, indicating that the platform and training were accessible to a wide range of digital proficiency levels. These findings suggest that the pedagogical design of VHEalthLab successfully supported equitable access to STEM innovation, independent of prior digital familiarity.

Qualitative data: Key findings

After completing the post-questionnaires, six of the participants agreed to answer the questions prepared for the interview, and three of them also participated in the focus group which was held online on the Zoom platform.

Shared strengths

- Practical classroom utility: VLs helped bridge abstract concepts (e.g., microscopy steps, cell division) with tangible learning, while reducing risks and costs of wet-lab work.
- Clear scaffolding: Module 1 and the Pedagogical Guidelines were valued for their step-by-step guidance and alignment with IBL.
- Intuitive structure: Teachers described the platform as easy to navigate and logically sequenced for lesson use.

Common challenges

- Curriculum alignment: Participants asked for tighter links to national syllabi and age-appropriate variants.

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- Assessment design: Requests focused on clearer, more varied formative checks and explanatory feedback.

- Clarity and language support: Some instructions and terms needed further clarification; teachers suggested glossaries and printable aides.

Enhancement priorities

- Strengthen usability and feedback: Add immediate, explanatory feedback; broaden item types; streamline navigation in labs where usability lagged (e.g., Light Microscopy).

- Deepen curricular coherence and differentiation: Provide explicit mapping to national standards, multiple difficulty tiers, and examples tailored to different school levels.

- Expand support materials and accessibility: Include glossaries of scientific terms, printable/low-bandwidth resources and clearer guidance for inclusive implementation

4.2.4. *Spain*

Context, participants and data collection
The implementation of VHEalthLab materials took place in higher Education with pre-service secondary science teachers enrolled in the Master's degree in Secondary Education (Experimental Sciences) at the University of Santiago de Compostela (USC).

Quantitative data: Key findings
A total of 30 participants completed the pre-questionnaire and the post-questionnaire. The pre-questionnaire was administered remotely one week before implementation; the post-questionnaire was completed in person on 20 May 2025 at the Faculty of Education of the USC.

The pre-questionnaire revealed mixed levels of digital readiness and prior exposure to virtual labs. While a strong majority felt confident using virtual labs, only one-third had worked with them before. Participants were moderately comfortable navigating online platforms.

Following engagement with the Pedagogical Guide, Module 1 and the first case study "Light Microscopy", the post-implementation feedback was uniformly positive: trainees described the platform as intuitive and the instructions as clear and easy to follow; they praised Module 1 and the Guidelines for effectively illustrating IBL and providing practical, context-rich examples. Participants particularly highlighted the

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Guidelines' emphasis on inclusion, gender equality strategies and step-by-step scaffolding, noting that this structure increased their confidence in implementing virtual laboratories in diverse classrooms.

At the same time, areas for improvement emerged around technical polish and interactivity: several respondents called for richer feedback during quizzes, a wider range of worked examples, and enhanced accessibility features (such as multilingual options). These insights point directly to the next steps in refining VHEalthLab's digital and learning environment.

Overall, the shift from initial curiosity before implementation to genuine motivation and interest afterward highlights the effectiveness of pairing an intuitive platform with inquiry-based pedagogy and inclusive materials, while also underlining the need for small adjustments and ongoing feedback to continuously improve VHEalthLab materials.

Qualitative data: Key findings

A total of 7 participants were selected to conduct both the interviews and the focus group. All had taken part in the virtual lab implementation, specifically Case 1 "Light Microscopy," along with Module 1 and the pedagogical guidelines.

The interviews were carried out before the focus group, ensuring that responses weren't influenced by others' opinions. The interviews consisted of individual written reports carried out remotely on 11th June 2025.

The semi-structured focus group was developed on-site and lasted 55 minutes. The participants, along with two facilitators, were seated around a table that allowed everyone to maintain visual contact with one another. All the interventions were audio recorded.

Shared strengths

- Intuitive navigation and clear support: Pre-service teachers found the VHEalthLab interface easy to use and valued the step-by-step instructions in both Module 1 and the pedagogical guide.

- Engaging multimedia: Videos, images, and dialogue-based scenarios made the virtual labs more immersive, and presenting mistakes as "learning moments" boosted confidence.

- Practical pedagogical resources: The guide's real-world examples, especially those on inclusion and gender equity, were highlighted as immediately applicable in secondary classrooms.

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Common challenges

- Limited interactivity and feedback: Participants requested richer interactive elements (like simulations or drag-and-drop tasks), clearer quiz feedback (showing correct answers and theory links), and freer back-button navigation.

- Overlap and length of materials: Some found content repetitive between Module 1 and the guide, and the guide's length initially felt daunting, suggesting a clearer split between theoretical background and practical application.

- Accessibility and avatar design: The on-screen avatar received mixed reviews, and several participants stressed the need for multilingual versions, glossary pop-ups, and offline options to ensure broad access.

Enhancement priorities

- Enrich interactivity: Integrate more hands-on widgets and scenario branching in lab activities.

- Strengthen feedback: Provide immediate, explanatory feedback on quizzes and add a forum for peer and instructor discussion.
- Expand accessibility: Release materials in multiple languages; include glossary tooltips and offline-friendly formats.

- Support diverse learners: Embed explicit, step-by-step instructions and consider audio/alt-text features for special-needs students.

5. Cross-sectional findings

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.

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

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5.1. Country-specific considerations

To complement the cross-sectional analysis, the table below highlights the most salient strengths and areas for improvement in Cyprus, Greece, Romania, and Spain, reflecting differences in curricula, digital readiness, and institutional contexts. These insights are intended to guide context-sensitive adoption and targeted refinements.

Table 2. Country Specific Strengths and Areas for Improvement for Virtual Laboratory Integration.

Country	Strengths	Areas for Improvement
Cyprus	• Step-by-step case design • Authentic media • Ready-to-use teacher assets (storylines, questions) • Certificate as motivator.	• Hidden controls and no quick “back” button • Small text/images • End-loaded quizzes without retry/explanations • Preference for qualitative over numeric scoring.
Greece	• Clear structure • Easy navigation • Multimedia aligned with objectives • Strong perceived fit for IBL in higher education.	• Need for richer, more varied scenarios and exposure to advanced instruments; • Request for corrective feedback that explicitly shows the right answer.
Romania	• Practical classroom utility • Clear scaffolding in Module 1/Guidelines	• Tighter links to national curriculum • More differentiated resources

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	• Approachable for varied digital skill levels.	• Clearer terms/glossary and printable supports.
Spain	• Very positive usability and clarity • Strong appreciation for inclusion and gender-equity guidance • Increased teacher confidence post-training.	• Richer feedback during quizzes • More worked examples • Multilingual options • Reduce overlap between Module 1 and the Guide

5.2. Strengths of VHEalthLab common across countries

- **Usability and clarity:** Interface and flow are intuitive; instructions are clear and easy to follow, lowering entry barriers for first-time users.

- **IBL alignment:** Module 1 and the Pedagogical Guidelines effectively translate IBL into actionable classroom practice (questioning, hypothesis building, evidence use).

- **Pedagogical value:** Step-by-step guidance, worked examples, and structured activity design increase teacher confidence to implement virtual labs.

- **Inclusive intent:** Guidance on gender equity and diverse learning needs is valued; the platform's structured pathways support learners who benefit from clear, paced progression.

- **Authentic multimedia:** Short videos, images, and scenario prompts increase realism and engagement, with "learning from mistakes" moments viewed positively.

- **Complementarity with wet labs:** Educators see VLs as a practical complement-expanding access, reducing cost/risk, and preparing students for physical labs.

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5.3. Recurrent challenges

- **Formative assessment and feedback:** Allow multiple attempts and provide immediate explanatory feedback (not just questionnaires at the end of the lab).
- **Navigation consistency:** Add a visible 'previous step' control, a clearer navigation trail, and consistent interaction patterns across all labs.
- **Interactivity and open exploration:** Enrich practical elements (e.g., branching decisions, drag and drop, microsimulations) and diversify scenarios to deepen inquiry.
- **Accessibility and language:** Enlarge fonts, icons, and key images; add captions and labels to silent clips; provide glossaries and printable resources.
- **Curriculum alignment and differentiation:** Adapt activities to national curricula, offer age/difficulty levels, and add optional advanced resources for higher education contexts.

5.4. Limitations and further considerations

The implementation of VHEalthLab across partner countries yielded actionable insights, while also revealing important limitations that should inform interpretation and future scale-up.

Differences in timing for implementation across partner countries. Pilots were conducted at different times and with evolving platform versions. For example, in Spain the laboratories had not yet been fully translated to Spanish at the time of testing, which influenced accessibility perceptions and underpins the recommendation to prioritize multilingual support. In parallel, several usability refinements were introduced during and immediately after the pilots (e.g., enlarging font sizes and key visuals; adding corrective feedback that shows the right answer in end-of-lab quizzes). Consequently, not all participants experienced the same feature set, and some concerns reported early on have since been addressed.

Scope of materials during testing vs. current availability. Early implementations focused on Module 1, the Pedagogical Guidelines, and four open-access labs: Laboratory Safety, Light Microscopy, Cell Structure and Function, Cell Division. Since then, the full suite of 14 virtual laboratories has been completed, expanding topical breadth and adding level-appropriate variants for secondary and higher education. Findings should therefore be read as a baseline for improvement; the present platform goes beyond what some cohorts evaluated.

Participants, context and transferability. Participant numbers and profiles varied by country (e.g., mixes of higher education tutors, in-service teachers, and pre-service teachers). Participation was voluntary, which may introduce self-selection

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bias toward digitally engaged educators. Sample sizes in some contexts were modest, limiting statistical generalization; results should be treated as indicative rather than definitive.

Instrument and data scope. The study relied on pre/post questionnaires and semi-structured interviews/focus groups. While this mixed approach captures perceptions and perceived competence, it is largely self-reported and short-term. Longer-term classroom impact (e.g., student learning outcomes, transfer to practice over a semester) was beyond the evaluation window and should be examined in subsequent studies.

Curricular heterogeneity. Implementation conditions differed (e.g., curricular frameworks, time allocation, class sizes, device constraints, language of delivery). These factors shape user experience and should be considered when comparing countries or extrapolating to new settings. Alignment to national curricula - requested particularly in Romania - remains a context-sensitive task.

Inquiry practices in VHEalthLab. By design, VHEalthLab uses guided pathways to scaffold IBL. Several stakeholders - especially in Greece - welcomed the clarity but wished for more open exploration. This reflects that guided inquiry supports consistency and inclusivity, however teachers may feel that it is not “open-ended”. Effective instruction by teachers (pre-/post-lab questioning, inquiry tasks) remains essential.

Accessibility and inclusion in progress. Early feedback highlighted needs around multilingual availability, glossary tooltips, clearer labels on media, and options supportive of diverse learners. Some of these have already been implemented (e.g., increased font sizes; improved quiz feedback), while others (e.g., expanded multilingual rollout, additional accessibility affordances) are in active development.

Ethical and procedural considerations. All contributions were collected with participant consent, anonymized for reporting, and used to improve the platform. Differences in local academic calendars and institutional procedures affected scheduling, which may have influenced participation rates and the breadth of classroom trialing.

5.5. Feedback driven and ongoing improvement

Building on the country implementations, VHEalthLab has already incorporated several concrete refinements and expanded its scope. In direct response to participant feedback, several key improvements have already been integrated into the VHEalthLab platform:

- **Deliver 14 VLs and 3 Teacher Modules:** In parallel, the platform progressed from the initial pilot set (Module 1, Pedagogical Guidelines, and four labs) to

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the full suite of 14 virtual laboratories and three training modules, with level-appropriate variants for secondary and first-year university use.

- **Formative Assessment and Feedback:** The assessment model has been significantly enhanced. End-of-lab quizzes now provide immediate, explanatory feedback for incorrect answers, transforming them from simple evaluations into meaningful learning opportunities aligned with IBL principles.

- **Improved Legibility and Accessibility:** To address concerns about readability, font sizes and key visuals have been enlarged across the platform, improving the user experience and making content more accessible.

Future Priorities

Considering the cross-country findings, the next phase focuses on:

- **Multilingual access and accessibility:** Continuous improvement of platform resources tailored to diverse learning needs (captions, clearer pop-up descriptions, larger controls, low bandwidth/offline options), reinforcing the inclusion of diverse types of learners and promoting gender-sensitive design.

- **Formative assessment and feedback:** Allow multiple attempts at assessment activities and provide immediate explanatory feedback aligned with IBL.

- **Curricular alignment and differentiation:** provide explicit mapping to partner-country curricula and offer tiered tasks/examples tailored to different ages and prior knowledge.

- **Navigation consistency and interactivity:** ensure common interface patterns across labs, expand scenario branching and hands-on widgets where pedagogically meaningful.

- **Teacher professional development:** continue supporting pre/during/post-lab organisation of IBL through training modules that include examples and practical cases.

6. Recommendations for the Integration of Virtual Laboratories in STEM and Health Education

The Erasmus+ VHEalthLab project operated under guiding principles that prioritised digital transformation, inclusion, and innovative teaching methods. Responding to the increasing demand for digital readiness and pedagogical resilience in higher education, accelerated by the rapid shift toward online and blended learning during the pandemic, the project developed open-access Virtual Laboratories (VLs) designed to cultivate students' digital skills through immersive, interactive learning

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experiences. These tools support the transition toward a more sustainable, future-oriented digital education ecosystem.

A strong commitment to inclusivity shaped the development of the VL resources. The project aimed to ensure universal accessibility, particularly for learners who face barriers to traditional higher education, including students with learning difficulties and those from culturally and linguistically diverse backgrounds. Special emphasis was placed on encouraging the participation of women and girls in STEM fields, supporting broader European goals for gender equality and inclusion. By removing structural and pedagogical barriers, VHEalthLab sought to guarantee equitable access to high-quality digital learning environments.

However, the transnational report identified challenges hindering the widespread and effective adoption of Virtual Laboratories across Europe. Digital infrastructure disparities persist, with countries such as Germany and Finland benefiting from advanced connectivity and immersive technology capacity, while others, including Romania and Greece, face limitations in access to essential digital equipment, particularly for VR-based applications. This unevenness creates inequitable learning conditions, placing students and educators in under-resourced contexts at a disadvantage.

In addition to infrastructural gaps, there remains a pressing need for enhanced faculty training and digital preparedness. Many educators accustomed to traditional teaching approaches lack confidence and competence in designing, facilitating, and evaluating virtual laboratory learning experiences. Resistance to pedagogical change further slows adoption. Without structured professional development and ongoing support, educators struggle to integrate VLs effectively into curricula.

Another barrier is the absence of standardised guidelines and evaluation frameworks. With no common national or institutional policies, VL implementation varies widely, making it difficult to benchmark quality, compare outcomes, or share models of excellence. Without recognised indicators of effectiveness, it is challenging for institutions to justify investment or commitment to VL adoption.

These findings point to an urgent need for coordinated policy action, targeted investment, and systemic support mechanisms. Policymakers, educational leaders, and technology providers must collaborate to bridge the digital divide, strengthen educator capacity, and establish common standards for quality and evaluation. Through such coordinated efforts, Europe can unlock the transformative potential of Virtual Laboratories to enhance STEM learning, deepen digital literacy, and equip students with the applied skills required in the 21st-century knowledge economy.

Based on the VHEalthLab findings, the following policy recommendations aim to facilitate the effective and equitable integration of Virtual Laboratories (VLs) into STEM and health education curricula across European higher education institutions.

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6.1. Standardised Guidelines and Evaluation Frameworks

The findings of the VHEalthLab project highlight the need for a coherent European approach to the design and evaluation of Virtual Laboratories. To achieve this, a Europe-wide task force composed of educational experts, technologists, and policymakers should be established to develop standardised guidelines that can be adopted across institutions. These guidelines should define technical specifications, pedagogical principles aligned with IBL, accessibility requirements based on Universal Design for Learning, and assessment metrics to ensure consistent quality. Introducing shared standards will promote interoperability and comparability, enabling institutions across different countries to integrate VLs with confidence and coherence.

6.2. Regional Teacher Academies for VL Integration

A second major recommendation concerns the systematic preparation of educators to use Virtual Laboratories effectively. The project evidence shows that both higher education teaching staff and pre-service and in-service secondary science teachers require structured professional development to adopt VLs in meaningful and pedagogically sound ways. Regional teacher academies would provide this support through hands-on training, mentoring, and ongoing guidance for curriculum integration. These academies would be supported by a cloud-based knowledge-sharing hub offering peer forums, updated teaching content, translated materials, and success stories, while a Train-the-Trainer model would ensure long-term scalability through locally embedded expertise. Strengthening educator capacity in this way will address current gaps in digital pedagogy and enable sustainable, locally led implementation.

6.3. Funding for Technological Infrastructure and Accessibility

To ensure equitable access to VL-based learning opportunities, European higher education institutions will require strengthened technological infrastructure. Dedicated funding streams should therefore be prioritised to improve internet connectivity, provide VR/AR equipment where relevant, and support the development of multilingual, adaptive, and accessible VL content for students with diverse backgrounds and learning needs. Such funding may be aligned with existing European collaboration and mobility programmes, helping ensure that no institution is disadvantaged by resource limitations. By reducing disparities in technological readiness, this investment will mitigate the digital divide and allow all institutions to engage effectively with Virtual Laboratories.

6.4. Cross-Border Collaboration and Resource Sharing

The VHEalthLab project also underscores the value of international collaboration for innovation and scalability. Encouraging universities to work together through grants and incentives would support the creation and sharing of open-access VL materials,

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fostering a culture of collective development rather than duplication of effort. This collaboration should include multilingual repositories, modular and adaptable VL components, and the exchange of best practices between countries and institutions. Such cooperation will allow Virtual Laboratories to evolve responsively, ensuring that they remain relevant to diverse contexts while benefiting from pooled expertise and resources.

6.5. Integration of VHEalthLab into National STEM and Digital Education Strategies

Finally, long-term sustainability will require that Virtual Laboratories become embedded within national education strategies. Future Erasmus+ and Horizon Europe initiatives could contribute to maintaining VHEalthLab repositories under open licences, but collaboration with Ministries of Education will be essential to scale and institutionalise their use. Policymakers should work with higher education institutions to establish curriculum integration guidelines, ensure recognition of VLs within accreditation processes, and secure ongoing funding for their development and implementation. Embedding VHEalthLab within strategic frameworks will position Virtual Laboratories as a core element of modern science education, ensuring continuity beyond project lifecycles and supporting systemic transformation across Europe.

6.6. Proposed Actions in case of an another funded programme arises - Roadmap (2026–2030)

The proposed roadmap for the implementation of Virtual Laboratories (VLs) across European higher education will become a guiding framework for a future initiative, contingent upon the availability of additional funding. This strategic plan will outline a phased and structured approach to ensure capacity-building, curricular integration, sustainability, and policy alignment. By moving from foundational preparation to system-wide embedding and long-term support mechanisms, the VHEalthLab roadmap is designed to facilitate the adoption of VLs at varying levels of institutional readiness while promoting coherence, scalability, and equitable participation across countries and sectors.

6.6.1. Phase 1: Foundations (2026) – Building Capacity and Setting Standards

In the first phase, the foundational groundwork for effective VL integration across Europe will be established. This will include standard-setting activities, pilot program development, and the initiation of teacher training structures. Work undertaken through the Erasmus+ VHEalthLab project—such as the establishment of an EU-wide task force and the review of existing VL resources—will form the basis for ongoing advancements. By 2026, regional Teacher Academy frameworks will be developed and launched in at least two regions per partner country (Cyprus, Greece, Romania, and Spain), accompanied by initial training focused on technical skills, inquiry-based pedagogy, and inclusive learning adaptation. This phase will also involve the collection of data from pilot academies, dissemination of guidelines through online platforms and national conferences, and allocation of preliminary infrastructure investment. Progress in this

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foundational stage will be assessed through indicators including published standardized guidelines, operational task force activity, functioning pilot academies, educator participation rates, and funding commitments.

6.6.2. Phase 2: Expansion and Curriculum Integration (2027–2028)

The second phase will focus on scaling implementation, embedding Virtual Laboratories within curricula, and expanding institutional involvement. In 2027, the Teacher Academy program will broaden to include additional faculty and institutions, refining training modules based on insights gained from the pilot period. Universities will be incentivized and granted funds to integrate VLs into core STEM and health programs, and to develop new course offerings and learning modules centered on virtual experimentation and inquiry-based practices. By 2028, a Europe-wide VL repository and collaboration platform will be launched to support shared development, resource exchange, and community engagement. Mid-term evaluations—utilizing student and faculty surveys, outcome measures, and focus group insights—will assess VL usage impact and identify opportunities for further refinement. Monitoring during this phase will concentrate on curriculum adoption levels, participation expansion, repository utilization, and positive learning and engagement outcomes.

6.6.3. Phase 3: Sustainability and Policy Influence (2029–2030)

The final phase will aim to institutionalize Virtual Laboratories within national and European education systems, ensuring ongoing support, funding, and recognition. In 2029, advocacy efforts will target the inclusion of VLs within national STEM and digital education strategies, while also securing dedicated research and development funding. Longitudinal studies will be conducted to evaluate the long-term effects of VLs on student motivation, academic success, and workforce preparation, thus informing continued refinement and validating policy relevance. In 2030, a European dissemination conference will showcase lessons learned, successful implementation cases, and future collaboration pathways. This phase will conclude with the development of a sustainability plan that addresses resource maintenance, long-term funding streams, community structures, and continued professional development pathways. Key performance indicators will include policy adoption by Member States, secured funding amounts, longitudinal evidence, and established sustainability frameworks.

6.6.4. Overarching Principles

Throughout all implementation phases, the roadmap will be guided by four cross-cutting principles. Flexibility and adaptability will ensure that institutions and countries can tailor VL adoption to their specific needs and contexts. Stakeholder engagement will guarantee the meaningful involvement of faculty, students, policymakers, and technology providers across all development stages. Evidence-based decision-making will support continuous monitoring, evaluation, and iterative improvement. Inclusivity and accessibility will ensure that all Virtual Laboratory resources are usable by diverse learners, including those with disabilities and those from underserved or marginalized communities. Together, these principles will ensure that VL integration strengthens European education systems in a fair, sustainable, and future-ready manner.

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6.7. Skills, Employability, and Workforce Readiness

The VHEalthLab initiative and the strategic roadmap outlined have significant implications for enhancing students' skill sets and their preparedness for the modern workforce. Virtual Laboratories, when integrated effectively into curricula, empower students with a unique combination of digital literacy, critical thinking, and problem-solving abilities. Students engaged in inquiry-based VL activities develop proficiency in using digital tools, analysing complex data, and making informed decisions, skills that are highly sought after in rapidly evolving STEM and health-related industries. The collaborative nature of many VL implementations further fosters teamwork and communication skills, preparing students to thrive in diverse and interdisciplinary professional environments.

By fostering this comprehensive skill set, VHEalthLab creates a vital link between education and employment, ensuring that graduates are well prepared to meet the demands of a dynamic and competitive job market. Improved analytical capabilities, increased confidence in digital tools, and the ability to apply theoretical knowledge to practical scenarios enhance students' competitiveness for career paths including research, healthcare, technology, and engineering. Supporting these activities will not only bridge the gap between education and the workplace but also contribute to Europe's long-term growth and innovation by cultivating a highly skilled and adaptable workforce ready to tackle future challenges.

7. Conclusions and Future Directions

The VHEalthLab project has demonstrated the significant potential of Virtual Laboratories to transform STEM and health education across European higher education systems. Through the development of open access, inclusive, and pedagogically robust Virtual Laboratories, the initiative has contributed to strengthening digital competence, enriching IBL, and expanding access to high quality practical experiences regardless of geographical, socioeconomic, linguistic, or physical barriers. The project has also highlighted the importance of integrating digital innovation with inclusive teaching practices to ensure that all learners, particularly those with fewer opportunities, can participate meaningfully in emerging digital education ecosystems.

The findings of the transnational analysis underscore both the opportunities and the challenges associated with large scale Virtual Laboratory adoption. While enthusiasm for digital experimentation and virtual learning is growing, disparities in infrastructure, educator readiness, and institutional policy frameworks continue to limit consistency and reach across Europe. These realities reinforce the need for continued investment, coordinated policy action, and long-term capacity building strategies to support systemic transformation. The policy recommendations and implementation roadmap outlined in Section 6 provide a structured pathway toward

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addressing these needs and create the conditions for scaling Virtual Laboratory integration sustainably and equitably.

Looking ahead, the further development of Virtual Laboratories will require ongoing collaboration between higher education institutions, ministries, technology providers, accreditation bodies, and European funding mechanisms. Continued research will be essential to deepen understanding of Virtual Laboratory impacts on learning outcomes, student motivation, skill development, and employability. Advancements in artificial intelligence, immersive simulation, multilingual adaptation, and personalised learning environments offer promising avenues for expanding the capabilities of Virtual Laboratory resources. Ensuring that these innovations remain accessible, inclusive, and pedagogically grounded will be central to their success.

Future initiatives should also focus on strengthening the alignment between virtual learning tools and labour market expectations. As Europe navigates rapid technological change, skills shortages in science, technology, engineering, and health sectors continue to intensify. Virtual Laboratories offer an effective bridge between theoretical knowledge and applied practice, helping students acquire analytical, digital, and collaborative competencies that are critical for workforce readiness. Supporting the continued evolution of VHEalthLab beyond the project lifecycle will contribute to a more agile, adaptable, and innovation driven European workforce.

In conclusion, the VHEalthLab project provides a strong foundation for the next phase of digital transformation in higher education. By continuing to expand Virtual Laboratory access, enhance educator preparation, invest in infrastructure, and embed Virtual Laboratories within national and European policy frameworks, Europe can accelerate progress toward a more inclusive, resilient, and future ready education system. The momentum generated through VHEalthLab represents not an end point, but a catalyst for ongoing innovation, collaboration, and educational renewal.

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