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Toward Sustainable Digital Education in Biology: Evaluating Educators' Perceptions and Adoption Intentions for a Virtual Laboratory Toolkit from Four European Contexts

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Abstract

Despite growing interest in Virtual Labs (VLs), limited research examines the factors influencing educators' willingness to adopt them through the lens of inquiry-based learning (IBL). This exploratory pilot study evaluates educators' interaction with the VHEalthLab VLs toolkit, examining their perceptions on usability, pedagogical value, IBL support, and intention to use. The study combines IBL, as a pedagogical lens, with the Technology Acceptance Model (TAM) within a Triple Bottom Line sustainability framework aligned with Sustainable Development Goals 4 and 10. Using an exploratory cross-sectional design with an embedded qualitative component, data were collected from seventy Biology educators across four European countries (Cyprus, Greece, Romania, Spain) through two structured questionnaires. Data analysis included descriptive statistics, Pearson correlations, directed content analysis, and joint display integration. Findings indicate that adoption intention was associated primarily with pedagogical rather than technological factors; IBL alignment showed the strongest association with intention to implement VLs ($r = 0.63$, $p < 0.001$), while perceived usefulness was most strongly associated with pedagogical materials ($r = 0.65$, $p < 0.001$). Assessment and inclusion functioned as quality criteria rather than factors associated with adoption intention. Educators consistently endorsed VLs as complements to physical laboratories, with their perceptions suggesting potential environmental, economic, and social sustainability implications within a blended model.

Keywords: sustainable digital education; educators' perceptions; biology education; virtual laboratories; inquiry-based learning; technology acceptance; STEM education; SDG 4; SDG 10; triple bottom line

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1. Introduction

The COVID-19 pandemic served as an inflection point that permanently accelerated the integration of digital technologies in education, transforming digital teaching from an add-on to a core component of educational practice [1–3]. Although the acute phase of the pandemic has passed, the structural changes, including institutional investment in digital platforms, increased educator familiarity with online tools, and policy shifts toward blended learning, continue to shape educational practice.

In this context, understanding educators' perceptions of digital laboratory tools is essential for informing their sustainable adoption of digital technologies in the post-pandemic educational landscape [1–4]. At the same time, sustainable digital education has gained ground by emphasizing inclusive, resource-efficient learning environments that support long-term pedagogical innovation [5,6]. These priorities align with the United Nations Sustainable Development Goals, particularly SDG 4 (quality education) and SDG 10 (reduced inequalities), which together call for equitable access to education and the removal of structural barriers to learning [7,8]. In this sense, digital educational technologies are increasingly evaluated not only in terms of instructional effectiveness but also in relation to their broader social role in promoting educational equity and accessibility. Assessing the sustainability of such digital education initiatives requires attention to their environmental, economic, and social dimensions, consistent with the Triple Bottom Line (TBL) framework increasingly applied in higher education contexts [9,10].

Virtual Labs (VLs), defined as interactive simulation environments that replicate real-world experimental processes in digital form, represent a particularly relevant example of such technologies [11]. VLs have been shown to extend access to laboratory-based learning experiences [12], reduce dependence on physical laboratory resources, and enable scalable implementation across diverse educational contexts [13,14]. In Science, Technology, Engineering, and Mathematics (STEM) education, technological advances and internet connectivity have expanded laboratory experimentation through virtual and remote laboratories [2]. Within this evolving landscape, VLs have emerged as a key innovation in science education, enabling interactive simulation-based experimentation that extends traditional laboratory boundaries [11]. Beyond their technical functionality, VLs also support inquiry-based learning (IBL) by enabling learners to engage in processes such as questioning, investigation, hypothesis testing, and evidence-based reasoning [13,14]. From this perspective, VLs offer a scalable and flexible approach to laboratory education, particularly relevant in disciplines such as biology and health sciences, where laboratory experimentation is central to conceptual understanding and scientific reasoning [15].

While the evidence base for the pedagogical and sustainability value of VLs is growing [16], most studies have primarily focused on student learning outcomes [17,18] with comparatively less attention given to educators' perceptions and adoption-related factors. This gap is especially evident in relation to integrated virtual laboratory ecosystems and in cross-national contexts, where comparative evidence remains limited. Educators, as the primary adopters and facilitators of digital technologies, play a central role in determining whether and how digital tools are implemented in classrooms. Thus, their perceptions are critical for understanding the conditions that enable or hinder sustainable adoption of VLs in education. The present study aims to examine educators' perceptions of an integrated virtual laboratory toolkit, with a specific focus on usability, pedagogical value, and support for IBL, as well as their intention to use such tools in practice. By doing so, the study seeks to identify the key factors that influence educators' acceptance of VLs within authentic educational contexts and across different national settings.

This current paper is structured as follows. Section 1 introduces the research problem, reviews the literature on virtual laboratories and educator adoption, presents the analytical

framework, and states the research aims and contributions. Section 2 describes the research design, participants, data collection instruments, analytical procedures, and ethical considerations. Section 3 presents the quantitative findings, the qualitative thematic analysis, and the integration of both data strands. Section 4 discusses the findings in relation to existing literature and acknowledges the study's limitations and future research directions. Section 5 presents the conclusions and practical implications.

1.1. Literature Review

1.1.1. Virtual Laboratories in Higher Education and Biology

VLs are technology-supported environments that simulate laboratory experiences, enabling users to manipulate equipment and conduct experiments digitally [19]. They are widely applied across STEM disciplines, including biology, chemistry, engineering, and medicine [20,21].

Research conducted during the COVID-19 period also demonstrated the potential of online STEM learning environments to support engagement and participation in digitally mediated science education [22]. Other studies support pedagogical advantages of VLs, including that they support visualization of complex phenomena, promote higher-order thinking and learner autonomy, and facilitate constructivist and collaborative learning [23–25]. By overcoming spatial, temporal, and safety constraints, VLs provide flexible, risk-free environments that enable repeated experimentation and hypothesis testing [26,27]. Their effectiveness is grounded in experiential learning theory [28] and constructivist perspectives emphasize interaction and active participation in knowledge construction [29]. Research on immersive digital environments has similarly highlighted the pedagogical affordances of interactive technologies for enhancing learner engagement and participation [30].

In biology education, where laboratory practice is fundamental to developing disciplinary knowledge, VLs are increasingly integrated to enhance engagement and support understanding of complex processes [30–33]. They serve as preparatory tools, enabling students to practice procedures and build confidence prior to physical laboratory work [34]. Notably, blended approaches combining VLs with physical laboratories appear particularly effective, improving knowledge, motivation, and self-efficacy [35]. Evidence consistently points to VLs as complementary tools that enhance rather than replace laboratory-based learning [36,37].

VLs contribute to all three sustainability dimensions of TBL in higher education. Environmentally, they reduce consumption of reagents, biological specimens, and single-use laboratory materials, lowering waste streams associated with physical experimentation [38,39]. Economically, they lower infrastructure and recurring material costs while enabling scalable delivery across institutions [40]. Socially, they address inequalities in access to laboratory resources by offering location-independent learning opportunities, supporting both SDG 4 and SDG 10 across contexts with varying levels of institutional resources [5,14].

While the evidence base for the pedagogical and sustainability value of VLs is growing, most studies have assessed these dimensions from the student perspective. Whether educators, as the primary adopters and facilitators, share these positive perceptions remains underexplored, particularly across different national and institutional contexts.

1.1.2. Educators' Attitudes & Adoption of Virtual Labs

Educators' attitudes strongly influence their willingness to adopt new technologies [41], while their perceptions are influenced by institutional conditions, professional experience, and pedagogical beliefs [42,43]. From the perspective of technology adoption theory, educators play a gatekeeping role in the dissemination of educational technologies [44]. Further, while student experience is often used to evaluate the effectiveness of

VLs, it is educators who make implementation decisions that determine whether a technology enters the classroom. The Technology Acceptance Model (TAM) positions behavioural intention as the most proximal predictor of actual use [41], and in educational settings, it is the educator's intention, not the student's, that governs whether a tool is selected, integrated into the curriculum, and sustained over time. This gatekeeping function is further shaped by pedagogical beliefs, which act as filters through which educators evaluate new tools against existing instructional approaches [43]. Recent studies examining teachers' digitalization practices highlight the importance of pedagogical readiness and contextual support in technology adoption [22]. This gap is significant, as adoption remains uneven due to limited infrastructure, insufficient training, and resistance to change [45,46]. Effective pedagogical use of VLs also depends on alignment with IBL principles where educators act as facilitators guiding students through structured inquiry processes [46]. Digital competence, the capacity to use technology effectively within pedagogical contexts, plays a critical role in successful integration [22]. Despite this, most VL research focuses on student outcomes, with fewer studies examining educators' perspectives [47].

The existing literature establishes that educator perceptions are shaped by pedagogical beliefs, digital competence, and institutional conditions. However, TAM-based studies of VLs have rarely incorporated pedagogical frameworks such as IBL as evaluative dimensions alongside technological constructs, leaving open the question of whether pedagogical alignment or technological usability is more closely associated with adoption intention.

1.2. Study Context and Analytical Framework

The current study is situated within the VHEalthLab project, a European initiative providing an open-access platform integrating fourteen VL activities in Biology with wide applicability in Health Sciences. The fourteen labs were selected following a European search of curricula across 28 countries and included 138 universities. A common standardized curriculum was proposed [48]. The VLs were designed using the OpenLabyrinth and CoffeeLMS platforms [49,50]. The platform includes pedagogical guidelines and training modules designed to support educators across higher and secondary education [51]. The toolkit was deployed across four European countries with differing levels of educational infrastructure and digital readiness. By evaluating it in these settings, the study contributes to an integrated understanding of the perceptual and pedagogical factors that support long-term adoption of digital laboratory technologies. This has implications for the environmental, economic, and social sustainability of STEM education [9,10].

This study combines two complementary theoretical perspectives: IBL and TAM. From a pedagogical standpoint, IBL serves as the conceptual lens to assess whether educators perceive VLs as environments that support key inquiry processes, including questioning, investigation, hypothesis testing, and evidence-based reasoning [15,52]. This is important as when supported by digital tools, IBL enables flexible, context-sensitive learning that extends beyond traditional classroom settings [4]. Herein, survey items were designed to reflect core IBL principles, enabling the analysis to examine whether VLs are perceived as meaningful tools aligned with constructivist learning approaches.

From a technology adoption perspective, TAM [41] provides a framework for understanding how perceptions shape adoption intentions. Beyond its core constructs of Perceived Usefulness and Perceived Ease of Use, TAM accommodates external variables relevant to educational contexts [31,53]. In this study, variables such as pedagogical value, learning design, usability, and IBL support are examined as factors shaping Behavioural Intention to Use, which represents the most immediate predictor of technology adoption.

Together, these three perspectives form a layered analytical structure. As described above, TAM provides the explanatory framework for examining adoption intention, while

IBL supplies the pedagogical criteria against which VL quality and design are evaluated. TBL, together with SDGs 4 and 10, provides the normative and interpretive context for discussing the sustainability implications of the findings. It should be noted that the study does not include TBL or the SDGs items that directly assess environmental, economic, or social sustainability outcomes. Rather, these frameworks are used to contextualize the broader significance of educators' perceptions and adoption patterns. This layered structure addresses a limitation of prior VL research, which tended to examine technological, pedagogical, and sustainability dimensions in isolation [14,22,38], leaving open the question of how these dimensions interact in shaping educators' adoption decisions within authentic implementation settings.

1.3. Research Aims

Despite the growing evidence base on VLs, research examining educators' perceptions remains limited, particularly regarding their views on VLs' contribution to IBL [14,54]. In addition, cross-country studies evaluating integrated VL toolkits that combine simulations with pedagogical and instructional support are especially scarce [14,26].

To address these gaps, the current study evaluates educators' perceptions of the VHEalthLab online toolkit, an integrated digital learning environment combining VLs with pedagogical support to complement Biology teaching in higher and secondary education. Drawing on data from educators across four European countries (Cyprus, Greece, Romania, Spain), the study aims to:

(1) Evaluate educators' perceptions of the toolkit in terms of usability, pedagogical value, and IBL support,
(2) Examine educators' intention to use the toolkit and its relationship with key perceived factors, and
(3) Identify conditions influencing acceptance and potential sustainable adoption.

With these aims, the current study makes several contributions to the existing literature. Theoretically, it integrates IBL as a pedagogical evaluative dimension within a TAM-based adoption framework, addressing the tendency in prior VL research to examine technological acceptance and pedagogical quality as separate concerns [14,39,44]. Further, by embedding a TBL sustainability lens, the study provides an analytical structure that connects adoption intention to environmental, economic, and social considerations, an integration not previously applied to educator-focused VL evaluations. Methodologically, the use of a joint display format to integrate quantitative and qualitative data from an educator evaluation of an integrated VL toolkit offers a replicable approach for mixed-source evaluative studies in digital education. Finally, the study provides pilot evidence from four European countries with differing educational infrastructure, extending the evidence base beyond the single-country and student-focused designs that characterize most existing VL research [1,51].

2. Materials and Methods

2.1. Research Design and Context of the Study

The pilot implementation of the VHEalthLab platform [48] was carried out within the VHEalthLab European research project, providing an authentic implementation setting in which educators' responses were grounded in actual use rather than hypothetical evaluation. Implementation activities were conducted across four pilot sites: (1) Cyprus, led by the University of Nicosia (UNIC); (2) Greece, led by Aristotle University of Thessaloniki (AUTH); (3) Spain, led by Universidade de Santiago de Compostela (USC); and (4) Romania, led by Ascendia.

The study adopted an exploratory, evaluative cross-sectional design with an embedded qualitative component. Two structured questionnaires with embedded open-ended items were administered to educators following their engagement with the toolkit, capturing both quantitative ratings and qualitative comments through a single data collection phase. Quantitative data were analyzed first, and qualitative responses were then used to explain, contextualize, and extend the quantitative findings. The cross-country design enabled identification of common patterns as well as context-specific observations related to pedagogical culture, institutional conditions, and digital readiness across the four participating countries.

2.2. Participants

The study population consisted of 70 Biology educators from the four European countries who participated in the pilot implementation and evaluation of the VHEalthLab online toolkit. Their feedback was implemented, and this is reflected in the updated platform. Participants were recruited through purposive convenience sampling via institutional networks and project partner channels in each country, following the ethical guidelines of the VHEalthLab project. Inclusion criteria, defined at project level, required involvement in Biology teaching at the HE or secondary education level.

The sample includes in-service HE and secondary education teachers as well as pre-service secondary science teachers, reflecting the authentic composition of the pilot implementation across different national and institutional contexts. This breadth of professional profiles is a deliberate feature of the study as VL adoption in practice depends on educators with varying levels of experience, pedagogical orientation and digital familiarity. As such, capturing perceptions across a variety of profiles strengthens the validity of the evaluation and its relevance to real-world implementation settings.

Detailed demographic data (e.g., age, gender, years of experience, specific teaching level) were not collected. This decision was made at the project level to ensure GDPR compliance across four national jurisdictions. The study's evaluative focus is on overall perceptions of usability, pedagogical value, and adoption intention that do not depend on demographic information. Still, the absence of these variables limits subgroup analyses and constrains the interpretation of qualitative patterns that appear to vary by professional experience. Where such patterns are noted in the findings, they are reported as qualitative observations rather than empirically confirmed subgroup differences. Per-country sample sizes were as follows: Cyprus (n = 20), Greece (n = 7), Spain (n = 29), Romania (n = 14). The unequal distribution of participants across countries prevents country-level comparisons. Accordingly, all analyses were conducted on the aggregated sample (N = 70), reflecting the geographic breadth of the pilot implementation rather than enabling cross-national comparative analysis.

2.3. Data Collection Instruments

Two structured questionnaires were developed by the VHEalthLab project consortium to capture educators' perceptions of the platform's pedagogical and technological characteristics and its potential for integration into teaching practice. Item development was informed by two established frameworks: (1) the System Usability Scale (SUS) [55], which guided the design of items assessing clarity, navigability, and platform functionality, and (2) the TAM [41], which informed items measuring Perceived Usefulness (PU), Behavioural Intention to Use (BI), and Attitude Toward Use (ATU). Items were adapted to the specific educational context of the VHEalthLab toolkit, incorporating dimensions relevant to the study's pedagogical focus, including IBL alignment, learning design, and

inclusion strategies. Supplementary Table S1 presents the full item-to-construct mapping for both questionnaires.

Both questionnaires were completed after participants had engaged with the online toolkit, including the VLs and corresponding pedagogical materials. The first questionnaire (Q1, 9 items) assessed educators' perceptions of the pedagogical guidelines and instructional module, with items aligned to SUS (clarity and accessibility of instructions) and TAM-PU (perceived usefulness for teaching practice, support for IBL, and consideration of inclusive teaching strategies). A single TAM-BI item captured educators' intention to use pedagogical materials. The second questionnaire (Q2, 15 items) evaluated educators' experiences with the VL activities, with SUS-aligned items addressing platform usability, navigation, and structural clarity, and TAM-PU items addressing pedagogical effectiveness, IBL alignment, assessment, learning design features, and inclusion. A single TAM-BI item measured intention to implement the VLs, while a TAM-ATU item assessed the perceived role of VLs in relation to physical laboratories. Both questionnaires also included open-ended items to capture qualitative comments that may be missed by the quantitative component.

All closed-ended items employed five-point Likert scales (1 = strongly disagree to 5 = strongly agree). Intention to use was measured as a single item in each questionnaire (Q1-item 9; Q2-item 13), a decision made to minimize respondent burden within the pilot implementation timeline. The estimated completion time for each questionnaire was approximately 10 min.

The instruments were developed by the project consortium for the specific evaluative context of the VHEalthLab toolkit and are aligned with, but not direct replications of, validated SUS and TAM scales. The full questionnaires and item-to-construct mapping are provided in Supplementary Materials. The alignment with established frameworks provides conceptual grounding for the analysis, but findings remain exploratory indicators, appropriate to the pilot context.

Internal consistency was examined using Cronbach's alpha and is reported alongside the results (Section 3).

2.4. Data Collection

A common data collection procedure was followed across all four participating countries to ensure methodological consistency and comparability of findings. Initially, educators participated in an introductory session, during which the objectives of the VHEalthLab project, the structure of the online toolkit, and the intended pedagogical use of the VLs were presented. Following that, participants were given access to the VHEalthLab online toolkit and were encouraged to interact with the platform, explore the VLs, and engage with the accompanying pedagogical guidelines and instructional materials. Finally, participants completed the two questionnaires, which captured their perceptions of the pedagogical materials, the VLs, and the overall usability and educational value of the toolkit.

2.5. Data Analysis

Microsoft Excel was used for all quantitative analyses. Given the exploratory and evaluative nature of the study, the use of descriptive statistics and bivariate correlations does not require advanced statistical software. Accordingly, the interpretation of results focuses on the direction and relative strength of associations between thematic dimensions and intention to use, without claims of predictive or explanatory power.

As discussed above, owing to the unequal participation rates across countries and relatively small national subsamples (ranging from n = 7 to n = 29), analyses were conducted on the aggregated dataset (N = 70) to ensure more stable and interpretable results. The

cross-country design therefore serves to broaden the ecological validity of the pilot rather than to support comparative analysis.

Questionnaire items were grouped into thematic categories informed by the SUS and TAM constructs underlying the item design (see Supplementary Material), with items grouped according to the pedagogical and technological dimensions they address. Where multiple TAM-PU items addressed a common pedagogical dimension (e.g., IBL alignment, inclusion strategies), they were combined into a single theme to enable more interpretable analysis. For Q1, thematic categories were clarity and accessibility (SUS), perceived usefulness (TAM-PU), pedagogical guidance and IBL (TAM-PU), inclusion strategies (TAM-PU), and intention to use (TAM-BI). For Q2, categories were usability, clarity, and platform functionality (SUS); perceived usefulness (TAM-PU); pedagogical value and IBL (TAM-PU); assessment effectiveness (TAM-PU); learning design (SUS + TAM-PU); inclusion strategies (TAM-PU); intention to use (TAM-BI); and perceived role of VLs in relation to physical laboratories, examined as two distinct constructs: replacement (TAM-ATU) and complementarity (TAM-PU).

Internal consistency reliability for multi-item themes was examined using Cronbach's alpha prior to further analysis. Descriptive statistics (means and standard deviations) were calculated at the theme level to summarize overall patterns. Pearson correlation analyses (two-tailed) were then conducted to explore associations between educators' intention to use (single-item measures: Q1—item 9; Q2—item 13) and the corresponding thematic dimensions. The use of Pearson correlations with mean scores derived from Likert-scale data is supported by evidence that parametric statistics perform robustly with ordinal data of this type, particularly when distributions are reasonably symmetric and sample sizes are adequate [56]. However, it should be noted that theme-level mean scores derived from two-item composites have limited variance, which may affect the stability of correlation estimates. In addition, all variables were self-reported through the same instruments at the same point, introducing the possibility that shared method variance inflates observed associations. These considerations reinforce the exploratory interpretation adopted throughout this study.

The statistical significance of each correlation was tested using the t-distribution with df = n − 2, and corresponding t-values are reported alongside the correlation coefficients. Statistical significance was primarily interpreted at the $p < 0.001$ level; where correlations met the $p < 0.01$ threshold but not $p < 0.001$, these are reported with the corresponding notation.

2.6. Qualitative and Integration Analysis

Data collected through the two questionnaires comprised both Likert-scale items and open-ended questions. The qualitative open-ended responses were then analysed using directed content analysis [57], with the quantitatively derived thematic categories serving as the primary coding framework. Where participant responses addressed constructs not captured by the Likert-scale items (e.g., digital equity, linguistic accessibility, cognitive diversity), these were identified inductively and reported as additional dimensions within the relevant thematic category.

Qualitative coding was conducted by one member of the research team (S.A.N) using the quantitatively derived thematic categories as the primary coding framework. Responses were independently reviewed by two additional team members (I.D. and E.D.) to check for consistency of interpretation. Discrepancies were discussed and resolved through consensus among the three coders. Where participant responses introduced dimensions beyond the predefined categories (e.g., digital equity, linguistic accessibility, cognitive diversity), these were identified inductively and included only when explicitly present in

the data. It should be acknowledged that the researchers' involvement in the VHEalthLab project may have influenced their interpretive lens. The use of a predefined, theory-driven coding framework was intended to constrain subjective interpretation and enhance analytical transparency. However, the absence of a full independent dual-coding process is recognized as a limitation, and future studies would benefit from more systematic inter-rater reliability assessment. It should also be noted that open-ended questionnaire items typically yield less qualitative depth than semi-structured interviews; however, they are appropriate for the evaluative purpose of this pilot study, where the primary aim was to contextualize and extend the quantitative findings.

Integration of the quantitative and qualitative findings followed the joint display format [58], mapping quantitative metrics against qualitative evidence for each theme in a joint display discussed in Section 3.3. The "Integrated Interpretation" column synthesizes the relationship between the two data strands, classifying each theme according to three categories: Convergent (qualitative confirms and explains the quantitative finding), Divergent (qualitative differs from the quantitative pattern), or Extending (qualitative adds dimensions not captured by the quantitative measures).

2.7. Ethical Considerations

The study was conducted in full compliance with ethical research standards and the General Data Protection Regulation (GDPR). Ethical approval was obtained from the Cyprus National Bioethics Committee (Approval No. EEBK ΕΠ 2024.01.103), the Research Ethics and Deontology Committee of the Aristotle University of Thessaloniki (Approval No. 145792/2024), Universidade de Santiago de Compostela Research Ethics Committee (Approval No USC 68/2024) and Ascendia Research Ethics Committee (Approval No. ASC6078). Participation was entirely voluntary, and data was collected anonymously to ensure confidentiality of responses.

3. Results

3.1. Quantitative Findings

Quantitative analyses were conducted on the aggregated sample (N = 70), as per-country sample sizes were insufficient for between-country comparisons. The results report descriptive patterns and correlational associations between thematic dimensions and intention to use. Methodological considerations are detailed in Section 2.5.

3.1.1. Evaluation of the Pedagogical Guidelines and Modules

To facilitate a structured analysis, the first questionnaire (Q1) was organized into five thematic dimensions reflecting key aspects of the pedagogical materials. The first four themes consist of two items each, while Intention to Use was measured as a single-item construct. Prior to the main analysis, internal consistency reliability was assessed for all multi-item themes using Cronbach's alpha ranging from acceptable to good across the themes, and indicating satisfactory internal consistency, despite minor variation in reliability across specific dimensions. The results are presented in Table 1.

All themes received positive ratings (M > 3.9), implying that educators viewed pedagogical resources favorably. The highest score was achieved by Theme 1, Clarity and Accessibility (M = 4.39), which means that the materials can be considered clearly organized. Despite this positive result, the moderate relationship between clarity and intention to adopt (r = 0.54) can be interpreted as a factor positively associated with intention to use, though not the strongest correlation. Theme 2: Perceived Usefulness showed the strongest correlation with intention to use (r = 0.65), although its reliability estimate was relatively

low ($\alpha = 0.66$), suggesting some heterogeneity in the two constituent items. Among all Q1 themes, usefulness was most closely associated with intention to use.

Table 1. Descriptive statistics and correlations with intention to use for Questionnaire 1 themes.

Theme	Items	k	Mean	SD	Alpha	r (Q9)	t	*p*
Theme 1: Clarity and Accessibility	Q1, Q2	2	4.39	0.80	0.79	0.54	5.22	<0.001
Theme 2: Perceived Usefulness	Q3, Q4	2	4.06	0.98	0.66	0.65	7.07	<0.001
Theme 3: Pedagogical Guidance and IBL	Q5, Q6	2	4.13	0.92	0.76	0.53	5.09	<0.001
Theme 4: Inclusion Strategies	Q7, Q8	2	3.93	0.92	0.76	0.53	5.10	<0.001
Theme 5: Adoption and Intention to Use	Q9	1	4.07	1.01	N/A	N/A	N/A	N/A

Notes: n = 70; df = 68 for all correlation tests. k = number of items per theme. Mean and SD were calculated using theme-level averages of constituent items measured on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Alpha = Cronbach's alpha for internal consistency of multi-item themes; values above 0.70 indicate acceptable reliability, whereas values between 0.60 and 0.70 may be considered adequate for exploratory research. r (Q9) = Pearson correlation between each theme score and the single-item measure of intention to use (Q9). t = t statistic testing the significance of the correlation coefficient, calculated with df = n − 2. All reported correlations were statistically significant at $p < 0.001$.

Theme 3: Pedagogical Guidance and IBL (M = 4.13) and Theme 4: Inclusion Strategies (M = 3.93) both received positive evaluations and showed moderate correlations with intention to use (r = 0.53 and r = 0.53, respectively). Finally, Theme 5: Adoption and Intention to Use had a rather high average score (M = 4.07) with noticeable variability (SD = 1.01).

3.1.2. Evaluation of the Virtual Laboratories

The second questionnaire (Q2) examined participants' perceptions of the VLs included in the VHEalthLab online toolkit. Following a similar analytical approach to Q1, items were grouped into eight thematic areas reflecting key aspects of the VL experience. Cronbach's alpha, descriptive statistics, and Pearson correlation analyses were used to summarize overall trends (Table 2).

Table 2. Descriptive statistics and correlations with intention to use for Questionnaire 2 themes.

Theme	Items	k	Mean	SD	Alpha	r (Q13)	t	*p*
Theme 1: Usability, Clarity and Platform Functionality	Q1, Q2, Q3, Q4	4	4.22	0.83	0.78	0.47	4.39	<0.001
Theme 2: Perceived Usefulness	Q5	1	3.66	1.13	N/A	0.57	5.72	<0.001
Theme 3: Pedagogical Value and IBL	Q6, Q7	2	3.98	0.93	0.75	0.63	6.69	<0.001
Theme 4: Assessment Effectiveness	Q8	1	3.74	1.06	N/A	0.45	4.16	<0.001
Theme 5: Learning Design	Q9, Q10	2	4.15	0.89	0.66	0.57	5.72	<0.001
Theme 6: Inclusion Strategies	Q11, Q12	2	3.35	1.22	0.75	0.43	3.93	<0.001
Theme 7: Adoption and Intention to Use	Q13	1	4.03	0.87	N/A	N/A	N/A	N/A
Theme 8a: Replacement	Q14	1	2.06	1.28	N/A	0.34	2.96	<0.01
Theme 8b: Complementarity	Q15	1	4.23	0.75	N/A	0.53	5.10	<0.001

Notes: n = 70; df = 68 for all correlation tests. k = number of items per theme. Mean and SD were calculated using theme-level averages of constituent items measured on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Alpha = Cronbach's alpha for internal consistency of multi-item themes; N/A indicates single-item themes for which internal consistency could not be estimated. r (Q13) = Pearson correlation between each theme score and the single-item measure of intention to use (Q13). t = test statistic for significance testing of the correlation coefficient, calculated with df = n − 2. Correlation strengths were interpreted using Cohen's (1988) conventions: small (r = 0.10–0.29), medium (r = 0.30–0.49), and large ($r \geq 0.50$) [59]. All correlations were statistically significant at $p < 0.001$, except Theme 8a ($p < 0.01$).

Theme 1 (Usability, Clarity and Platform Functionality) received the highest average rating (M = 4.22, SD = 0.83), indicating that educators found the platform well-structured and accessible. Its correlation with intention to use was medium (r = 0.47). Theme 2 (Perceived Usefulness) had a lower mean (M = 3.66, SD = 1.13) with the second highest variability across all themes, suggesting heterogeneity in educators' perceptions of the VLs' practical value. Its correlation with intention to use was large (r = 0.57). Theme 3 (Pedagogical Value and IBL) showed the strongest correlation with intention to use across all Q2 themes (r = 0.63), with a mean of 3.98 (SD = 0.93). This suggests that perceived alignment with inquiry-based pedagogy was the dimension most closely associated with adoption intention in this sample.

Theme 4 (Assessment Effectiveness) showed a medium correlation with intention to use (r = 0.45) and a mean of 3.74 (SD = 1.06). Theme 5 (Learning Design) received the third highest mean (M = 4.15, SD = 0.89) and showed a large correlation with intention to use (r = 0.57), suggesting that the perceived structural quality of the VL activities was positively associated with adoption intention. Theme 6 (Inclusion Strategies) received the lowest mean across all themes (M = 3.35, SD = 1.22) and the highest variability, with a medium correlation with intention to use (r = 0.43).

Theme 7 (Adoption and Intention to Use) had a mean of 4.03 (SD = 0.87), indicating generally positive adoption intentions among participating educators. The perceived role of VLs in relation to physical laboratories was examined through two constructs. Theme 8a (Replacement) received the lowest mean of any theme (M = 2.06, SD = 1.28), with a small-to-medium correlation with intention to use (r = 0.34, $p < 0.01$); educators did not perceive VLs as replacements for physical laboratories. Theme 8b (Complementarity) received the highest mean of any theme (M = 4.23, SD = 0.75) with a large correlation (r = 0.53), indicating strong endorsement of VLs as complements to physical laboratory work.

3.2. Qualitative Findings

3.2.1. Educators' Views on Pedagogical Materials

Qualitative findings on the pedagogical materials (Table 3) demonstrate a relatively positive perception, along with several aspects that require further refinement. Clarity and structure were mentioned as strengths, as participants valued clear language and logical organization. Participants approved the structure of the modules, focusing on their interactive design. However, they noted that the guideline document was too long and partly repetitive. Qualitative responses suggest that perceived usefulness may have varied by teaching experience, though demographic data were not collected to confirm this pattern. Educators who self-identified in their open-ended responses as relatively new to teaching described the materials as directly helpful for understanding how to implement VLs, while those who indicated greater experience regarded the materials as informative but less necessary for their own practice.

The IBL framework was found to be strong conceptually in terms of explaining the process of inquiry and the role of educators. On the other hand, there is a demand for practical recommendations that would include relevant examples and assistance with assessment. Participants found inclusion as an important factor that positively contributes to the quality of materials. Specifically, the emphasis is put on the topic of gender equality and consideration of different needs. Nevertheless, guidance was seen as insufficiently focused, as there were further concerns about digital inclusion, language barriers, and cognitive issues. Adoption intention was mostly positive yet conditional in nature.

Table 3. Thematic Analysis of Qualitative Findings: Pedagogical Guidelines and Modules.

Theme	Key Thematic Areas	Advantages	Concerns	Quote
Theme 1: Clarity and Accessibility	Language clarity, structural accessibility	Language was praised across countries; clear terminology and logical sequencing; well-organised sections; Module 1 preferred for its interactive format	Guidelines document (33 pages) perceived as heavy, content overlap identified, lack of visual summaries and schematic formatting	*"The division into sections greatly facilitates the understanding of inquiry, how to create an activity, how to make the most of the virtual laboratory"*
Theme 2: Perceived Usefulness	Materials valued, professional orientation, practical teaching support, contextualized, teacher experience	Materials valued for professional orientation and practical teaching support, useful for understanding what VLs can do and how to adapt teaching, directly helpful for novice teachers, informative for professional development	Gap between professional orientation and operational readiness, materials inform a decision already made rather than motivating one from scratch, experienced educators found this less useful	*"The examples are very useful for new professors like me, who don't have a lot of experience"*
Theme 3: Pedagogical Guidance and IBL	Theory behind IBL, practical implementation guidance, active learning	IBL concepts clearly explained, teacher roles well explained, inquiry cycle and connections to active learning recognised, situated learning approach valued	Worked classroom examples missing, rubrics for inquiry competencies requested, socio-scientific contexts not addressed	*"The guide and the module teach the 'what' and the 'why' about IBL; but the explanations about how to implement it in the classroom have been more brief and generic than desirable"*
Theme 4: Inclusion Strategies	Inclusion, gender gap, diverse learning, classroom application	Gender gap and diverse learning needs addressed in the materials, awareness of equity in science valued, examples were a useful addition	Need more guidance for classroom use, Module 1 covers inclusion less than the guidelines; unmeasured dimensions raised by participants: digital equity, linguistic accessibility, cognitive accessibility, and differentiated content by student level	*"Be more specific when explaining what characteristics we should consider to promote inclusivity. It is not just about having access to more images and more time to create a truly inclusive space"*
Theme 5: Adoption and Intention to Use	Generally positive disposition, conditional use	Willingness to adopt expressed, some respondents reported no reservations, most respondents described the platform as recommendable to colleagues	Conditional use based on addition of more practical examples, more specific IBL scaffolding, and improved assessment feedback, and professional development needs raised	*"I have no recommendations for the guide or the training module. I consider that both are very well designed"* *"If I had to implement an activity in the classroom using this platform right now, I would encounter difficulties and questions that neither the guide nor the module have answered"*

3.2.2. Educators' Views on Virtual Laboratories

For VLs, the same directed content analysis approach was applied across the eight thematic categories. VLs were viewed positively overall, while also noting some points for improvement (Table 4). Usability and structure of VLs were appreciated, especially step-by-step organization, while some navigation issues and a lack of time flexibility were pointed out. Further, educators valued the role of VLs in conducting complicated experiments, as well as preparation for lab work, though they were uncertain about their extra value compared to conventional presentations. Features that were inquiry-based were appraised positively. On the other hand, the biggest issue was identified in assessment due to the lack of feedback. The learning design aspect was also evaluated positively, while improvement suggestions concerned audiovisual aspects and text-to-picture balance. The issue of inclusion was also discussed, and the need for contextualization was emphasized. The intention to use the technology seemed positive but depended on improvements in interactivity, assessment, and instructional issues.

Table 4. Thematic Analysis of Qualitative Findings: Virtual Laboratories.

Theme	Key Thematic Areas	Advantages	Concerns	Quote
Theme 1: Usability, Clarity and Platform Functionality	Positive usability baseline, interface issues identified as improvement priorities rather than fundamental problems, navigation, layout	Intuitive navigation, clear layout, step-by-step design prevents information overload, hidden content in tabs appreciated, easy to manipulate	Timing limits too short for secondary education students, no backward navigation, drag-and-drop exercises reset unexpectedly, window-in-window design hinders video playback, font size and contrast insufficient, animated GIF distracting for students with ADHD	*"Going step by step makes it more pleasant and doesn't overwhelm with information overload, so hiding information in tabs seems like a good idea"*
Theme 2: Perceived Usefulness	VL practical value, teaching needs, preparation, demonstration	Useful for demonstrating content difficult to show physically, enables repetition without material waste, provides effective preparation before real lab sessions	Criticised as too similar to passive demonstration, gap between virtual and physical lab experience	*"There are different virtual labs that can show experiments that would be difficult to do in schools"* *"The platform offers more of a visual support, like a video tutorial, rather than a tool that could be considered a virtual laboratory"*
Theme 3: Pedagogical Value and IBL	Conceptual IBL alignment, barriers to full inquiry realisation	Error-based learning valued, hint-based guided questioning praised, realistic errors (air bubbles, dirty lenses), student-centered approach recognised	Limited branching and student autonomy, absence of hypothesis formulation or open-ended investigation opportunities, collaborative inquiry features missing	*"The teacher never gives the answer to the problem but always gives hints and tries to connect the virtual activities to real-world phenomena, so it's easier for the students to understand"*
Theme 4: Assessment Effectiveness	Most consistent cross-country critique in the entire study, absence of corrective feedback universally identified as the primary concern	Quiz structure provides a checkpoint for self-evaluation, the presence of assessment at the end was valued	No correct answers shown after errors, no explanatory rationale provided, answers cannot be changed before submission, assessment concentrated at the end rather than distributed throughout the activity	*"At the end of the evaluation you cannot see the correct answer. There is no feedback other than your score"*
Theme 5: Learning Design	Structural design, video resources appreciated, improvement suggestions (enhancement-oriented)	Learning objectives valued and seen as motivating, situated learning design with characters and dialogue engaging, video tutorials complement procedural understanding, step-by-step interface provides clarity	Suggestions for closer camera recording and step-specific captioning, audio narration requested for procedural videos, excessive text volume relative to visual content, particularly for secondary-level audiences	*"The complementation of all protocols with a video helps students understand rather than merely memorize"*
Theme 6: Inclusion Strategies	Perceived adequacy, concerns vary by country (reflecting different educational priorities)	Female guide avatar positively noted as a step toward gender representation, some visual and accessibility features appreciated	Avatar perceived as normatively attractive and stereotypical, differentiated resources by student level needed, digital equity concerns for homework use, animated elements problematic for students with ADHD	*"She looks like a Barbie, completely normative. It would be much better to use a more realistic woman, and preferably one not made with artificial intelligence. From a feminist perspective, it would be interesting to include a real female scientist"*
Theme 7: Adoption and Intention to Use	Positive with conditions, educators envision using VLs with improvements	Willingness to implement expressed, platform recognised as having strong potential, described as a rich and flexible resource by some respondents, would recommend to colleagues	Conditions include assessment feedback, greater interactivity and simulation depth, more practical IBL guidance, and stronger inclusion provisions.	*"VHEalthLab offers a rich and flexible platform that effectively supports inquiry-based learning"* *"It is still a work in progress and still needs improvements"*

Table 4. *Cont.*

Theme	Key Thematic Areas	Advantages	Concerns	Quote
Theme 8a: Replacement	Rejection grounded in pedagogical reasoning about the nature of laboratory learning	None (no respondent in any country argued that VLs should replace physical laboratories)	Physical labs provide tactile, social, and experiential dimensions that VLs cannot replicate, students need to manipulate materials and learn from physical mistakes, hands-on experience seen as foundational to science education	*"This type of practice should be carried out in a real laboratory where students can manipulate materials, make mistakes, and redo samples"*
Theme 8b: Complementarity	Educators see VLs as extending and enriching physical lab work (most consensual finding across all countries and all themes)	Pre-lab preparation builds foundational knowledge, repetition without material waste, environmental benefit noted (reduced waste and material consumption), safe exploration of procedures, asynchronous access for students needing more time, bridges limited laboratory hours or equipment	Complementary value depends on pairing with real lab sessions, specific deployment models suggested (individual, group, flipped classroom)	*"Learning these basic notions beforehand allows for better use of time in the laboratory"*

3.3. Integration of Quantitative and Qualitative Data

This section presents the integrated findings from the quantitative and qualitative datasets, examining how the two strands converge, diverge, or extend one another (Table 5). By bringing them into dialogue, it highlights emerging patterns and insights that would not be apparent when each dataset is considered in isolation.

Three main patterns emerge from the integration of the two datasets. Findings indicate that factors associated with adoption differ depending on the component of the VHEalth-Lab online toolkit evaluated: Pedagogical Guidelines & Modules or VLs. The strongest association with the intention to use pedagogical material was perceived usefulness, while alignment with IBL appeared as an important, although secondary, criterion. In the case of VLs, alignment with IBL showed the strongest association, while the perception of usefulness became secondary but still important. It is interesting to note that the reasons mentioned above are justified by the findings of the qualitative comments provided by the educators.

Second, divergence between qualitative and quantitative findings highlights dimensions related to educational quality rather than adoption. This pattern is most evident in assessment and inclusion. Both themes generated substantial qualitative feedback, yet they are weaker correlates of adoption in the quantitative analysis. Educators consistently emphasized the importance of feedback mechanisms and inclusive design, particularly in relation to student experience, equity, and accessibility. However, these concerns appear to function more as quality criteria than as factors closely associated with adoption intention. Qualitative data also extends the construct of inclusion by identifying additional dimensions, including digital equity, linguistic accessibility, and cognitive diversity, not captured by quantitative measures.

Table 5. Joint Display of Integrated Findings (Q1 & Q2).

Component Evaluated	Theme	Quantitative Findings	Qualitative Insights	Assessment	Integrated Interpretation
Pedagogical Guidelines & Modules	Clarity & Accessibility	Highest mean; moderate correlation	Language and structure consistently praised; concerns about length and overlap	Convergent	The high scores are confirmed by consistent qualitative praise. Clarity operates as a baseline condition: educators need to understand the materials before they can use them, but clarity alone does not drive adoption.
Pedagogical Guidelines & Modules	Perceived Usefulness	Strongest correlation of intention of use	Valued for professional orientation; variability by experience level	Convergent	The strong correlation aligns with qualitative evidence that adoption intention is most closely associated with perceived practical value. Educators who saw direct relevance to their teaching expressed clearer willingness to adopt.
Pedagogical Guidelines & Modules	Pedagogical Guidance & IBL	High mean; moderate correlation	Conceptually strong but lacking practical implementation guidance	Extending	A clear distinction emerges: educators value IBL conceptually but do not find it sufficiently operational. The gap between understanding IBL and being able to apply it explains the weaker link with adoption.
Pedagogical Guidelines & Modules	Inclusion	Lowest mean; moderate correlation	Inclusion acknowledged but perceived as general and non-operational	Extending	The lower quantitative rating aligns with qualitative concerns about lack of specificity. The qualitative data extend the construct by identifying additional dimensions (e.g., digital equity, linguistic accessibility) not captured in the survey.
Pedagogical Guidelines & Modules	Adoption	High mean with variability	Ranges from immediate adoption to conditional acceptance	Convergent	The variability in intention corresponds directly to qualitative conditions. Educators' requirements (e.g., practical guidance, clearer application) align with the strongest association for adoption.
Virtual Labs	Usability & Functionality	Highest mean; moderate correlation	Positive usability; specific technical issues reported	Convergent	The high usability ratings are supported by qualitative feedback. Reported issues are perceived as refinements rather than barriers, explaining the moderate (not dominant) role in adoption.
Virtual Labs	Perceived Usefulness	Lower mean; strong correlation	Divided perceptions of value (interactive vs. passive experience)	Extending	The variability in ratings is explained by differing user experiences. Educators who perceived genuine interactivity reported higher usefulness and stronger adoption intention.
Virtual Labs	Pedagogical Value & IBL	Strongest association of intention to use	Strong engagement; missing inquiry elements identified	Extending	The strongest correlation reflects the central role of pedagogical alignment. Educators who recognised inquiry-based features were significantly more likely to adopt, even when implementation was not fully realised.
Virtual Labs	Assessment	Moderate correlation	Most consistent and frequent criticism (lack of feedback)	Divergent	A divergence emerges: although assessment generated the strongest qualitative critique, it plays a secondary role in adoption decisions. This indicates that assessment is prioritised as a quality issue rather than an adoption driver.
Virtual Labs	Learning Design	High mean; strong correlation	Positive structure and multimedia support; minor balance issues	Convergent	Both data sources converge in identifying learning design as a strength. The positive perceptions of structure and support are positively associated with increased adoption intention.
Virtual Labs	Inclusion	Lowest mean; high variability	Multi-dimensional and context-dependent concerns	Divergent + Extending	A dual pattern emerges: divergence in importance and extension of the construct. Inclusion is discussed extensively but is weakly linked to adoption, while qualitative data reveal additional dimensions not captured quantitatively.
Virtual Labs	Adoption	High mean	Positive but conditional intentions	Convergent	Qualitative conditions closely match the strongest quantitative predictors (IBL, usefulness, design), reinforcing a consistent pattern of conditional adoption.
Virtual Labs	Replacement	Lowest mean; weak correlation	Strong rejection across participants	Convergent	Complete convergence: educators clearly reject replacement. Adoption intention does not depend on viewing VLs as substitutes for physical labs.
Virtual Labs	Complementarity	Highest mean; strong correlation	Strong consensus with concrete use cases	Convergent	Strongest convergence across datasets. Educators not only endorse complementarity but describe specific implementation scenarios, confirming that adoption is grounded in a blended model.

Third, a strong consensus emerges regarding the complementary role of VLs. Both datasets consistently indicate that they are not perceived as substitutes for physical labs but

as complementary tools. While replacement is clearly rejected, complementarity is strongly endorsed and supported by concrete use cases, including preparation, repetition, safe experimentation, and flexible access. This convergence suggests that adoption is grounded in a blended pedagogical model in which virtual and physical laboratory experiences coexist. Overall, the integration demonstrates that while quantitative results identify the relative importance of adoption factors, qualitative findings explain how and why these factors shape educators' decisions. Together, they provide a coherent account of adoption as a function of both practical use and pedagogical alignment, moderated by considerations of educational quality.

4. Discussion

The significance of this study lies in providing empirical evidence on educators' perceptions of the VHEalthLab online toolkit and VLs. These digital learning activities are designed to complement and support laboratory-based Biology teaching across higher education while investigating exploratory associations between intention to use and key perceived factors. By integrating an IBL perspective with the TAM framework and situating the analysis within the sustainability lens of the TBL [8,9] and SDGs 4 and 10, the study moves beyond purely technological interpretations of adoption and foregrounds the pedagogical and sustainability-related logic underlying educators' decisions.

Findings indicate that the perceptions of educators about the VHEalthLab toolkit are primarily pedagogically rather than technologically driven. Using the IBL model as a point of reference, educators' perceptions are strongly associated with the extent to which VLs promote a structured inquiry process. Consistent with the existing literature, the effectiveness of IBL environments is not inherent to their exploratory nature but depends on the degree to which they are pedagogically scaffolded to support questioning, hypothesis formation, and evidence-based reasoning [14,15,57]. The present findings reinforce this position, suggesting that VLs are not perceived as self-sufficient learning environments but as tools whose value is contingent upon their instructional integration.

At the same time, while educators acknowledge the alignment of the toolkit with IBL principles, it can be seen from the quantitative and qualitative data obtained that this recognition does not automatically translate into adoption intention. The moderate, not large, correlations between all factors related to IBL and intentions to use suggest that alignment with inquiry principles is necessary but not sufficient for adoption.

This pattern is particularly evident in the Q1 correlation analysis, where general perceived usefulness emerges as showing the strongest association with intention to use the pedagogical framework, exceeding IBL alignment. This result is consistent with the theoretical perspective of TAM [41], although it also adds a different dimension to it by suggesting that usefulness of pedagogical resources is perceived in a broad professional sense rather than strictly in relation to specific instructional approaches. Clarity and usability can be considered as enabling factors, without which engagement will not occur, but which will not be sufficient to promote intention. As can be seen from the results, educators should first engage with resources to evaluate their usefulness. It should be noted that, in the absence of demographic data, claims regarding variation in perceived usefulness by professional experience are based on self-reported qualitative comments rather than on confirmed subgroup differences. While these qualitative observations are consistent with prior literature indicating that novice and experienced educators respond differently to pedagogical support tools [60], they should be interpreted with this limitation in mind.

Intention to use in relation to the VLs (Q2) shows a different picture altogether. Contrary to Q1, where perceived usefulness showed the strongest association, in intention to

use VLs, it becomes secondary, and alignment with IBL becomes dominant. This indicates that there are distinct standards by which an educator evaluates the tool at hand. When it comes to structured pedagogical material, perceived usefulness is most closely associated with adoption intention. However, when it comes to interactive digital tools like VLs, it is alignment with IBL that shows the strongest correlation. This distinction is particularly important, as it highlights that intention to use is not a stable construct but varies depending on the type of educational resource under consideration. This differential suggests that educators apply different evaluative lenses to different types of resources, suggesting that pedagogical support materials should prioritise immediate practical utility, while VLs should prioritise pedagogical alignment with inquiry-based approaches.

This finding also has implications for how TAM is applied in educational technology research. While TAM provides a suitable theoretical framework, the present results show that the relative importance of its core constructs (Perceived Usefulness vs. Behavioural Intention) is not fixed but context-dependent, varying by resource type. This suggests that future applications of TAM in educational contexts should account for the nature of the resource being evaluated. This observation, however, should be interpreted in light of the study's instrument design. As the questionnaires were project-developed and aligned with rather than replications of validated TAM scales, the construct boundaries reflected in the thematic categories may not fully correspond to those established in prior psychometric work. Replication with validated instruments would be needed to confirm whether the differential pattern holds across measurement approaches.

Further insights into these associations emerge from the qualitative analysis. Specifically, the toolkit was repeatedly characterized by educators as sound in its conceptual framework yet lacking in pedagogical substance, thus pointing towards the necessity of further assistance in putting into practice the ideas of IBL. In this way, we can better understand how highly positive perceptions regarding the pedagogical worth of the tool do not automatically translate into high levels of intention to use. In this sense, intention to use appears to be mediated by the perceived feasibility of implementation, not only by perceived value. This finding aligns with previous work emphasizing that the effectiveness and sustainability of online learning environments depend not only on technological functionality but also on instructional design quality and implementation support [61]. When educators evaluate the adoption of a tool for their own practice, they appear to give more weight to whether it aligns with their pedagogical goals, whether it meets their teaching needs, and whether its design supports learning effectively. This indicates that the pathway to increased adoption runs through deepening the inquiry aspects of the VLs.

An important finding that emerged from the integration analysis concerns the role of assessment and inclusion as quality criteria rather than adoption factors. Assessment effectiveness generated the most consistent qualitative critique across all four countries, with educators uniformly identifying the absence of corrective feedback as a significant concern. However, assessment showed only a medium correlation with intention to use, ranking among the weaker associations in Q2. This divergent pattern reveals that educators distinguish between features they consider important for educational quality and features that influence their personal adoption decisions. Assessment appears to be a priority for student learning experience but a secondary consideration in whether educators themselves would adopt the tool.

A similar pattern emerged for inclusion, as inclusion strategies received the lowest quantitative ratings in both questionnaires and the highest variability yet generated extensive qualitative elaboration. Furthermore, an important aspect addressed in this study is that inclusion is identified as a significant factor associated with intention to use. The association between inclusion and intention to use VLs indicates that educators show

a preference for technologies that can be adapted and customized to different learning contexts. Beyond the survey items, educators identified additional dimensions of inclusion not captured quantitatively, including digital equity, linguistic accessibility, cognitive diversity, and gender representation. These extended dimensions connect directly to SDG 10's concern with reducing structural inequalities and to the social sustainability dimension of the TBL framework [10]. As such, the contribution expands traditional theories based on TAM by adding the element of adaptability and inclusiveness in technology use within pedagogical settings. While previous extensions of TAM have mentioned other variables used in explaining behavioral intention, namely self-efficacy and social influence [58,60–63], the explicit role of inclusion has not yet been fully explored. The present results therefore suggest the need to further conceptualize adoption as a socio-pedagogical process associated with contextual responsiveness and inclusivity.

Finally, the findings regarding the perceived role of VLs in educational practices indicate that educators reject the idea of VLs as replacements for physical laboratories and instead emphasize their complementary role. While this approach is consistent with the experiential foundations of IBL, which emphasize hands-on experience [64], it also takes into account the supplementary benefits of using VLs as tools that allow students to gain new insights regardless of limitations associated with time, space, and safety [57,65]. Given the high degree of agreement on the complementarity of VLs, the implementation of virtual learning environments would prove most effective when they are considered part of an integrative model that enhances traditional approaches [35,37,66].

This complementarity finding also carries direct sustainability implications when viewed through the TBL lens. Environmentally, a blended model in which VLs handle preparation, repetition, and conceptual exploration while physical labs focus on hands-on experiences optimizes resource use, reducing consumption of reagents, specimens, and single-use materials [38,39]. Economically, VLs lower recurring material costs and infrastructure requirements, enabling scalable delivery across institutions with varying resource levels [40]. Socially, VLs extend access to laboratory experiences for students in under-resourced contexts, supporting both SDG 4 (quality education) and SDG 10 (reduced inequalities) [8,14]. The consistency of this finding across four European countries with differing educational infrastructure strengthens the case for VLs as transferable, scalable tools for reducing between-country inequality in laboratory education. Integrating such scalable virtual tools directly supports ongoing efforts to standardize biology laboratory curricula across European undergraduate health education programs [51]. Furthermore, as previously demonstrated by the successful deployment of web-based virtual patients, specialized interactive simulations offer proven pedagogical value when embedded within these integrated digital frameworks [53].

Taken together, intention to use is influenced by the interaction among a number of factors, namely pedagogical value, usefulness, relevance, and inclusiveness. Although TAM offers a suitable theoretical framework, the research shows that its explanatory capabilities can be further increased by integrating pedagogical models, including IBL. The latter implies that adoption should be viewed as a process where pedagogy plays a critical role in decision-making. From a sustainability perspective, the long-term viability of digital educational tools depends on whether educators will actually adopt and maintain them. Institutional readiness and implementation capacity have also been identified as critical factors influencing the successful integration of emerging technologies in higher education settings [67]. Technology that is procured but unused represents wasted economic resources and failed institutional investment. By identifying the specific perceptual and pedagogical factors associated with adoption intention, this study contributes to the evidence base for designing digital education initiatives that are sustainable in environ-

mental (resource-efficient), economic (scalable and cost-effective), and social (equitable and inclusive) terms [9,10]. These insights may inform future approaches to sustainable digital educational initiatives. Their effectiveness depends not only on technological functionality but also on pedagogical suitability.

Limitations and Future Research

The sample size is modest (n = 70), based on purposive convenience sampling, and shows unequal country representation. Still, such sampling and sample size are considered appropriate for pilot studies, which primarily aim to assess feasibility and refine research procedures rather than produce generalizable findings [68]. Nonetheless, the imbalance precludes country-level analysis and limits the extent to which findings can be attributed to specific national or institutional contexts. Future research should include larger and more balanced samples across participating countries to enable meaningful cross-national comparisons and to examine whether the patterns observed at the aggregate level hold within specific educational and institutional contexts. Longitudinal studies tracking whether adoption intentions translate into actual implementation behaviour would be particularly valuable.

In the current study, detailed demographic data were not collected, precluding subgroup analyses. Future studies may also benefit from collecting demographic data to enable subgroup analyses, and integrating student outcome measures alongside educator perceptions to provide a more comprehensive account of VL effectiveness. It should be noted that all independent and dependent variables were collected from the same respondents via the same instruments at the same time point, which introduces the risk of common-method variance potentially inflating observed correlations [69]. The cross-sectional design captures intention to use at a single time point and cannot assess whether intentions translate into actual adoption behavior over time. Finally, the analysis is correlational and as such the associations reported should not be interpreted as causal or predictive relationships.

Further, the questionnaires were developed by the project consortium for this specific evaluative context, informed by SUS and TAM constructs but not constituting validated replications of these instruments. While the alignment with established frameworks provides theoretical grounding, the thematic categories used in the analysis should be understood as context-specific groupings rather than psychometrically confirmed constructs. Future studies employing validated TAM and usability instruments would strengthen the generalizability of the findings.

5. Conclusions

This study evaluated educators' perceptions of the VHEalthLab online toolkit and VLs from four European countries, examining usability, pedagogical value, IBL alignment, and intention to use within a framework combining IBL and TAM, situated within the sustainability lens of the Triple Bottom Line. As an exploratory pilot study, the findings should be interpreted as initial indicators that warrant further investigation.

Herein, three principal findings emerge. First, adoption intention was associated primarily with pedagogical factors rather than technological ones, with IBL alignment showing the strongest association with intention to use VLs and perceived usefulness showing the strongest association for pedagogical support materials. This suggests that educators apply different criteria depending on resource type, a finding that extends the application of TAM in educational contexts.

Second, assessment effectiveness and inclusion strategies function as quality criteria rather than primary adoption factors. While both generated extensive qualitative concerns, particularly the absence of corrective feedback in assessments and the need for broader

inclusion provisions (digital equity, linguistic accessibility, and cognitive diversity), their quantitative associations with adoption intention were moderate. These dimensions connect directly to SDG 10 and the social sustainability dimension of the TBL, signaling that VLs design should address structural inequalities to fulfill its sustainability potential.

Third, educators consistently endorsed VLs as complements to, rather than replacements for, physical laboratories. This consensual finding is consistent with a blended laboratory model that could optimize resource use across the three TBL dimensions, potentially reducing environmental waste, lowering economic costs, and extending social access to laboratory education. However, as the study measured educators' perceptions rather than sustainability outcomes directly, these implications are derived from the interpretive application of the TBL framework and would require empirical verification.

These findings carry practical implications for the design of sustainable digital education initiatives. Developers of VLs toolkits should prioritize depth of inquiry-based features over interface sophistication, embed formative assessment with corrective feedback, and design for inclusive access across diverse contexts. Institutions considering VLs adoption should invest in pedagogical support that translates IBL principles into actionable classroom guidance, as educators' perceptions of practical feasibility mediate the pathway from positive evaluation to adoption intention. The convergence of findings across the four pilot countries, despite different educational infrastructures, suggests that there is potential for integrated VL toolkits as a transferable model. When pedagogically grounded and designed for inclusion, such toolkits may help advance quality, equitable, and sustainable STEM education aligned with SDG 4 and SDG 10.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18136445/s1. Table S1A: Questionnaire 1 mapping—Pedagogical Guidelines and Modules; Table S1B: Questionnaire 2 mapping—Virtual Laboratories; Questionnaire 1: Evaluation of the Pedagogical guidelines and the Modules; Questionnaire 2: Evaluation of the VLs. Refs. [41,55] are cited in the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

VLs	Virtual Labs
IBL	Inquiry-based learning
IBSE	Inquiry-Based Science Education
HE	Higher Education
STEM	Science, Technology, Engineering, and Mathematics
ICT	Information and Communication Technologies
TAM	Technology Acceptance Model
GDPR	General Data Protection Regulation
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