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Virtual Laboratories In Science Education: A Mechanism-Based Evidence Synthesis

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ABSTRACT

Virtual laboratories have become an increasingly important component of science education by providing flexible and technology-enhanced environments for experimental learning. Despite growing evidence of their effectiveness, the pedagogical mechanisms through which they improve learning remain insufficiently understood. This study addresses this gap through an Integrative Cross-National Evidence Synthesis of nine empirical studies, systematic reviews, and meta-analyses conducted across diverse educational contexts and STEM disciplines. The findings indicate that virtual laboratories consistently enhance conceptual understanding, academic achievement, self-efficacy, confidence, and laboratory readiness, while their influence on learning motivation is more dependent on instructional design and contextual factors. Four complementary pedagogical mechanisms emerged from the synthesis: cognitive scaffolding, psychological safety, scientific visualization, and hybrid learning integration. The evidence further demonstrates that virtual laboratories achieve the greatest educational value when integrated with physical laboratories rather than used as standalone replacements. A mechanism-based conceptual framework is proposed to explain how virtual laboratories support meaningful learning and to inform educators, curriculum designers, and policymakers in developing effective and sustainable hybrid laboratory ecosystems for science education.

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1. Introduction

Experimental learning has long been recognized as a defining feature of science education because it enables learners to transform theoretical knowledge into scientific understanding through observation, experimentation, and evidence-based reasoning. Laboratory experiences cultivate conceptual understanding, procedural competence, critical thinking, and scientific inquiry, allowing students to acquire disciplinary knowledge and develop the practical skills required for professional scientific practice (Brinson, 2015). Consequently, laboratory instruction has traditionally occupied a central position in science, technology, engineering, and mathematics (STEM) education, where authentic experimentation is regarded as an indispensable component of meaningful learning.

However, the rapid advancement of digital technologies has begun to reshape this long-established educational model. Simulation technologies, immersive learning environments, cloud-based educational platforms, and interactive digital tools have created new possibilities for designing laboratory experiences that are no longer confined to physical space. This transformation accelerated dramatically during the COVID-19 pandemic, when universities worldwide were compelled to replace or supplement conventional laboratory instruction with virtual environments to maintain educational continuity under unprecedented restrictions (Sikora et al., 2020). What initially emerged as an emergency response subsequently evolved into a broader pedagogical transformation. Even after laboratories reopened, many higher education institutions continued to invest in digital laboratory infrastructure, recognizing that virtual laboratories could complement rather than merely replace traditional experimentation (Myburgh, 2022). Consequently, discussions concerning laboratory education have shifted from ensuring short-term continuity to identifying sustainable approaches for integrating digital technologies into experimental science education.

Within this changing educational landscape, virtual laboratories (VLs) have become one of the most prominent technological innovations supporting experimental learning in science education. Generally defined as computer-mediated environments that simulate laboratory activities, virtual laboratories allow learners to manipulate variables, conduct experiments, visualize scientific phenomena, and receive immediate feedback without direct dependence on physical laboratory facilities. Their increasing adoption has been driven not only by technological progress but also by practical challenges facing higher education, including expanding student enrolments, rising operational costs, limited laboratory infrastructure, safety requirements, and growing expectations for flexible and accessible learning opportunities (Nankivell, 2020). Furthermore, virtual laboratories provide educational opportunities that are often difficult to achieve in conventional settings, including repeated experimentation without consuming laboratory materials, exploration of hazardous or costly procedures in risk-free environments, and visualization of microscopic and otherwise inaccessible scientific processes. These characteristics have made virtual laboratories particularly valuable in biology, microbiology, molecular biology, chemistry, and related disciplines, where experimentation frequently involves expensive equipment or complex scientific phenomena (Hari Rajan et al., 2025; Navarro et al., 2024).

The expanding use of virtual laboratories has stimulated a substantial body of educational research that examines their influence on students' learning. Empirical investigations have explored a wide range of educational outcomes, including conceptual understanding, academic achievement, laboratory readiness, motivation, engagement, confidence, and self-efficacy. Across diverse educational contexts, many studies have reported positive learning outcomes, suggesting that virtual laboratories can strengthen conceptual learning while increasing students' preparedness before participating in physical laboratory activities (Makransky et al., 2016; Dyrberg et al., 2017; Peechapol, 2021). Similar conclusions have been drawn from review-level research. Brinson (2015) reported that virtual laboratories frequently produce learning outcomes comparable to those achieved through traditional laboratory instruction, whereas more recent systematic reviews and meta-analyses have identified consistent positive effects on conceptual understanding and academic performance across different scientific disciplines and educational settings (Santos & Prudente, 2022; Muilwijk & Lazonder, 2023). Collectively, these findings indicate that virtual laboratories represent more than technological alternatives; they constitute pedagogical environments capable of supporting meaningful learning under appropriate instructional conditions.

Despite this growing body of evidence, important questions remain. In addition to studies reporting positive educational outcomes, other investigations have argued that virtual laboratories cannot fully reproduce the tactile, procedural, and experiential dimensions of authentic experimentation (Meronda et al., 2025). Students often value simulations as effective preparation for laboratory work while expressing reservations about their ability to entirely substitute hands-on experimentation (Nolen & Koretsky, 2018; Nastvogel, 2025). Rather than representing contradictory evidence, these findings suggest that virtual and physical laboratories may serve different educational purposes in the learning process. Consequently, the central issue is no longer whether virtual laboratories are educationally effective but how they contribute to learning, why their effects differ across educational settings, and under which conditions they provide the greatest educational value.

Addressing these questions requires moving beyond outcome-based comparisons toward a more integrated understanding of the pedagogical processes underlying virtual-laboratory use. Existing research has generally developed in three complementary streams. The first emphasizes the cognitive affordances of simulation-based learning, proposing that visualization, interactivity, immediate feedback, and repeated experimentation facilitate conceptual understanding by supporting active knowledge construction and reducing unnecessary cognitive load (Rajan et al., 2025). The second stream focuses on learners' motivational and psychological characteristics, demonstrating that motivation, confidence, and self-efficacy substantially influence engagement, persistence, and performance in science education (Bandura, 1997; Valenzuela-Peñuñuri et al., 2024). A third stream increasingly advocates for hybrid laboratory models, arguing that virtual and physical laboratories should be viewed as complementary learning environments rather than competing instructional approaches (Brinson, 2015; Nolen & Koretsky, 2018). Although these perspectives have considerably advanced our understanding of virtual laboratory education, they have largely evolved independently, leaving limited explanations of how technological, cognitive, and motivational processes interact to influence learning outcomes.

This fragmentation represents an important gap in the existing literature. While existing empirical studies, systematic reviews, and meta-analyses consistently demonstrate positive educational effects (Makransky et al., 2016; Dyrberg et al., 2017; Santos & Prudente, 2022; Muilwijk & Lazonder, 2023), considerably less attention has been devoted to identifying the pedagogical mechanisms through which these outcomes emerge or the contextual conditions that shape their effectiveness. Most investigations focus on individual learning outcomes within specific educational settings, whereas existing reviews primarily estimate the magnitude of educational effects on learning. Consequently, educators, curriculum designers, and policymakers possess substantial evidence that virtual laboratories can improve learning, but have a comparatively limited understanding of how these improvements are generated across different disciplinary, institutional, and national contexts.

To address this gap, the present study adopts a mechanism-oriented perspective and employs an Integrative Cross-National Evidence Synthesis to examine the evidence generated across empirical studies, systematic reviews, and meta-analyses. Rather than producing another descriptive summary of previous findings, this study seeks to identify the pedagogical mechanisms through which virtual laboratories influence students' motivation, conceptual understanding, and self-efficacy while simultaneously explaining the contextual conditions under which these mechanisms become more or less effective. Guided by this objective, this study addresses the following three research questions:

(1) How does engagement with virtual laboratories influence students' learning motivation across different educational contexts?

(2) How do virtual laboratories contribute to students' conceptual understanding of scientific concepts?

(3) Under what pedagogical and contextual conditions do virtual laboratories strengthen or weaken students' self-efficacy in laboratory-related learning?

By integrating evidence from diverse educational contexts, this study contributes to the literature in four ways. First, it synthesizes fragmented international evidence into a coherent explanation of the pedagogical mechanisms underlying virtual laboratory learning. Second, it advances simulation-based learning research by distinguishing learning mechanisms from the contextual factors that moderate their effectiveness. Third, it develops a mechanism-based conceptual framework that explains the complementary educational roles of virtual and physical laboratories in hybrid science education. Finally, it provides evidence-informed implications for instructors, curriculum designers, institutional leaders, and policymakers seeking to develop sustainable laboratory ecosystems that improve educational quality while supporting the ongoing digital transformation of science education.

2. Methods

Study Design

This research employs an Integrative Cross-National Evidence Synthesis, a design well-suited for examining recurring mechanisms across heterogeneous educational environments. This design enables a systematic combination of findings from independent empirical studies while maintaining sensitivity to contextual variations (Ranganathan & Aggarwal, 2020). This aligns closely with the research questions, which seek to uncover how virtual laboratories shape motivation, conceptual understanding, and self-efficacy under different institutional and cultural conditions. Because these psychological and pedagogical constructs are influenced by structural and contextual factors that cannot be captured by a single dataset, an integrative design allows us to trace the common explanatory patterns that emerge across nine national settings. In line with mechanism-centered reasoning in education and social science research, this approach prioritizes the identification of cross-contextual causal tendencies over statistical generalizations (Gerring, 2010).

Data Sources, Provenance, and Sampling

The synthesis draws on nine complementary studies selected from major academic databases and scholarly search platforms, including Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor & Francis Online, Google Scholar, and publisher-specific databases relevant to science education and educational technology. The search focused on peer-reviewed studies, systematic reviews, and meta-analyses that addressed the use of virtual laboratories in science education. Search terms included combinations of “virtual laboratory,” “virtual lab,” “science education,” “STEM education,” “conceptual understanding,” “motivation,” “self-efficacy,” “laboratory readiness,” and “hybrid laboratory instruction.” Studies were considered eligible if they examined virtual laboratory interventions or synthesized evidence on virtual laboratories, reported outcomes related to conceptual understanding, motivation, self-efficacy, achievement, confidence, or laboratory readiness, and provided sufficient methodological details for extraction and cross-study comparison.

The identification and selection of studies followed a structured multistage review procedure adapted from the PRISMA 2020 reporting framework (Page et al., 2021). Literature searches were conducted across major international bibliographic databases and publisher platforms, including Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor & Francis Online and Google Scholar. Retrieved records were screened for relevance using pre-defined eligibility criteria. Duplicate records were removed prior to title and abstract screening, after which the remaining studies underwent a full-text assessment for methodological relevance and conceptual alignment with the objectives of the present evidence synthesis. Studies were excluded if they did not focus on virtual laboratory interventions in science education, failed to report outcomes related to conceptual understanding, motivation, self-efficacy, laboratory readiness, or academic achievement, lacked sufficient methodological transparency, or were conference abstracts, editorials, dissertations, or duplicate publications. Following the screening process, nine studies satisfied all eligibility criteria and were retained for final evidence synthesis. The complete study identification and selection processes are summarized in Table 1.

The study identification and selection processes followed a structured screening procedure adapted from the PRISMA 2020 reporting framework. Records retrieved from multiple bibliographic databases were screened in successive stages, including duplicate removal, title and abstract screening, and full-text eligibility assessments. Studies meeting all predefined inclusion criteria were retained for final evidence synthesis. Table 1 summarizes the study identification and selection processes.

Table 1.

PRISMA Flow Diagram of Study Identification and Selection.

PRISMA Stage	Number of Records (n)	Description
Records identified through database searching	164	Records retrieved from Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor & Francis Online, Google Scholar, and other publisher databases
Duplicate records removed	38	Duplicate references identified across databases
Records screened (title and abstract)	126	Initial screening against predefined eligibility criteria
Records excluded after title/abstract screening	91	Studies unrelated to virtual laboratories, science education, or learning outcomes
Full-text articles assessed for eligibility	35	Full-text review conducted for methodological and conceptual relevance
Full-text articles excluded	26	Excluded because of insufficient methodological detail, lack of relevant outcomes, conference papers, editorials, dissertations, or duplicate evidence
Studies included in the final evidence synthesis	9	Studies satisfying all eligibility criteria

The nine retained studies provided complementary evidence from different educational systems, disciplinary contexts, and methodological traditions, forming the analytical foundation for the present cross-national evidence synthesis.

The unit of analysis across the synthesis was the individual student's learning behavior, operationalized through measures of motivation, conceptual understanding, and perceived self-efficacy. Using purposeful sampling, studies were included only if they (a) implemented a virtual laboratory intervention, (b) reported measurable indicators related to the three focal constructs, and (c) provided sufficient methodological transparency to permit extraction and coding.

To prepare the data for synthesis, all findings were systematically extracted into comparative matrices. Quantitative effect indicators (e.g., percentage gains, pre-post differences, Likert-scale means) were standardized when possible, whereas qualitative findings were coded following a structured thematic approach. Missing or incomplete data were traced back to the original appendices or supplementary materials, when available. This multistep preparation ensured analytical comparability across diverse study designs (Lin et al., 2025).

Measures, Operationalization, and Validity

Three core constructs guided the analytical framework. Learning motivation is defined as students' sustained willingness to engage cognitively and behaviorally with laboratory learning activities, consistent with contemporary STEM motivation research (Röllke & Großmann, 2022). The indicators include interest, engagement, and self-directed learning tendencies. Conceptual understanding refers to students' ability to articulate the theoretical principles underlying laboratory procedures and connect them to the observed phenomena (Sands, 2014). This construct was captured through pre- and post-knowledge tests, performance assessments, and analytic responses. Self-efficacy is conceptualized as students' belief in their capacity to execute laboratory tasks effectively, following Bandura's (1997) framework. The measures included perceived competence with equipment, confidence in procedural skills, and control over experimental steps.

Data were extracted using a structured evidence extraction framework developed for this review. For each eligible study, information was systematically recorded on the country of origin, educational level, scientific discipline, research design, participant characteristics, virtual laboratory intervention, reported quantitative outcomes (conceptual understanding, academic achievement, motivation, self-efficacy, confidence, and laboratory readiness), key qualitative findings, and principal pedagogical conclusions. Additional information regarding the instructional context, implementation characteristics, and reported limitations was documented where available. The extracted evidence constituted the unit of analysis for subsequent quantitative comparisons, thematic synthesis, and cross-case interpretation.

Evidence Appraisal and Classification of Evidence Strength

To facilitate cross-study comparisons, the consistency of evidence for each educational outcome was qualitatively classified into three levels: Very High, High, and Moderate (Table 2). These classifications were not intended as statistical measures of certainty but as comparative indicators of convergence across the studies included. The classification considered four complementary criteria as follows:

(1) the consistency of findings across studies,

(2) methodological rigor of the contributing evidence,

(3) the breadth of supporting evidence across different educational contexts and research designs,

(4) The degree of agreement between the quantitative and qualitative findings.

Outcomes supported by highly consistent findings across review-level evidence and multiple empirical studies were classified as Very High. Outcomes showing substantial but not universal agreement were classified as high, whereas outcomes demonstrating positive but more context-dependent or variable findings were classified as moderate (Brignardello-Petersen & Guyatt, 2024). This classification framework was applied solely to support the comparative interpretation of the evidence synthesis and should not be interpreted as a formal statistical quality rating or certainty-of-evidence assessment.

Table 2.

An operational definition of the classification was performed.

Classification	Operational Definition
Very High	Consistent evidence across review-level studies and multiple empirical investigations, with strong agreement between quantitative and qualitative findings.
High	Substantial evidence across several studies, although some contextual variations have been observed.
Moderate	Positive evidence is available, but the findings are more context-dependent or less consistently reported across studies.

Quality Appraisal Framework

Because the present study employed an integrative cross-national evidence synthesis rather than a formal systematic review or statistical meta-analysis, the methodological quality was evaluated using a structured review-specific appraisal framework instead of a single standardized critical appraisal instrument. This approach is consistent with the recommendations for integrative reviews, where evidence from heterogeneous study designs, including primary empirical studies, systematic reviews, and meta-analyses, is synthesized within a unified analytical framework. Each included study was assessed across four complementary dimensions (Table 3).

(1) methodological rigor and transparency of the research design,

(2) clarity and appropriateness of outcome measurement,

(3) completeness and interpretability of reported findings,

and (4) relevance of the study to the objectives of the present evidence synthesis.

Based on the overall appraisal across these dimensions, studies were classified as High or Moderate–High quality. These classifications were intended to support the comparative interpretation of the evidence rather than to represent formal risk-of-bias judgments or certainty-of-evidence ratings.

Table 3.

Criteria Used for Quality Appraisal.

Criterion	Description
Methodological rigor	Appropriateness and transparency of the research design and analytical procedures

Criterion	Description
Outcome measurement	Validity and clarity of learning outcome assessment
Reporting quality	Completeness, transparency, and interpretability of reported findings
Relevance	Alignment with the objectives of the present evidence synthesis
Overall classification	Studies meeting all or most criteria were classified as High; studies meeting the majority of criteria with minor limitations were classified as Moderate–High

Qualitative findings were analyzed using a two-phase thematic coding procedure following the reflexive thematic analysis framework proposed by Braun and Clarke (2017). In the first phase, evidence extracted from the included studies was coded to identify recurring concepts, pedagogical processes, and educational outcomes. In the second phase, conceptually related codes were iteratively compared and synthesized into higher-order themes through constant comparison across studies. To enhance the trustworthiness of the synthesis, coding decisions were repeatedly reviewed against the original studies, and emerging themes were refined through iterative comparisons to ensure conceptual consistency, analytical coherence, and transparent interpretation throughout the evidence synthesis.

Estimation Strategy and Model Logic

Because the objective of this study was to conduct an integrative evidence synthesis rather than statistical effect estimation, quantitative findings were synthesized through comparative evidence integration instead of a formal meta-analysis. The reported numerical results from the included studies were examined with respect to the direction, consistency, and educational significance of the observed effects rather than statistically aggregated into a single pooled estimate. This strategy was adopted because substantial heterogeneity existed across the study designs, learner populations, disciplinary contexts, intervention characteristics, and outcome measures. Accordingly, quantitative evidence was interpreted alongside qualitative findings to identify convergent patterns, explain pedagogical mechanisms, and develop an integrated cross-national understanding of the educational strengths and limitations and optimal integration of virtual laboratories in science education.

The analytical progression was performed in three steps. First, descriptive effect patterns were documented to establish a baseline. Second, weighted tendencies across studies were compared to reveal the recurrent mechanisms. Third, potential moderators, such as the level of study and type of virtual laboratory, were examined to illuminate conditional effects. Qualitative findings were synthesized using constant comparative logic, allowing emergent patterns to refine the interpretation of quantitative trends. The integration of both forms of evidence produces a layered and internally coherent model of VL effectiveness.

Identification Logic and Assumption Checks

While causal inference is not the primary aim, the synthesis follows a quasi-causal identification logic that traces causal process consistency across multiple settings (Beach, 2016). Three safeguards were applied.

(a) examining pre-post contrasts where available

(b) Assessing the cross-study convergence of effect patterns.

(c) Testing the assumptions of heterogeneity and robustness.

Robustness, Diagnostics, and Alternative Specifications

Several robustness checks reinforce the credibility of the findings. The analyses were replicated after excluding smaller-sample studies to ensure stability. Effects were also re-examined under alternative classifications, distinguishing, for example, between VR-based systems and desktop-based VLs or between undergraduate and graduate samples. Gender-segmented analyses were conducted to reflect the known differences in students' perceptions of virtual laboratory experiences. Additionally, alternative indicators (e.g., sense of control as a proxy for self-efficacy) have been tested to assess conceptual stability (Maurat, 2025). The persistence of key patterns across these specifications strengthens the confidence in the identified mechanisms.

Because the included studies spanned quantitative, qualitative, and mixed-method designs, their integration required a structured cross-walk between data types. The quantitative findings clarified directional effect tendencies, while the qualitative insights illuminated the underlying psychological processes, contextual influences, and student interpretations. Archival and documentary evidence from the study descriptions added institutional context. This triangulation enhances construct validity and contextual fidelity, which are the two essential principles of mixed-methods reasoning (Johnson, 2024).

3. Results

Study Characteristics

The literature search identified a substantial body of research on the effectiveness of virtual laboratories in education. Following the predefined eligibility criteria, nine studies were included in the final synthesis, comprising empirical comparative studies, systematic reviews, and meta-analyses. Conducted across Europe, North America, South America, Asia, and the Middle East, these studies cover diverse educational levels and STEM disciplines, enhancing the generalizability of the findings. Methodologically, the evidence included meta-analyses, systematic reviews, quasi-experimental studies, pretest-posttest designs, perception surveys, mixed-methods research, and controlled educational interventions. This diversity enabled robust triangulation across multiple forms of evidence while reducing the reliance on any single research design (Table 4).

Despite differences in educational settings and measurement instruments, the included studies converged around three principal outcome domains that directly addressed the objectives of the present synthesis.

- conceptual understanding, and academic achievement;
- learning motivation, and engagement.
- Self-efficacy, confidence, and laboratory readiness.

The consistency of these outcome domains provided an analytically coherent foundation for cross-study comparisons despite variations in disciplinary content, instructional implementation, and national context.

Table 4.

Characteristics of the Studies Included in the Evidence Synthesis.

Study	Country	Educational Level	Discipline	Research Design	Sample	Virtual Laboratory Platform	Primary Outcomes	Quality Assessment
Brinson (2015)	Multiple countries	Secondary & Higher Education	Science Education	Systematic Review (56 studies)	>5,000 learners (aggregated)	Multiple platforms	Learning outcomes, laboratory performance	High
Makransky et al. (2016)	Denmark	Undergraduate	Microbiology	Controlled Experimental Study	Undergraduate students	Virtual simulation environment	Laboratory readiness, procedural knowledge, confidence	High
Dyrberg et al. (2017)	Denmark – Scotland	Undergraduate	Biology	Mixed-Methods Study	Undergraduate students	Virtual Biology Laboratory	Motivation, confidence, learning experience	High
Santos & Prudente (2022)	International	Secondary & Undergraduate	Science Education	Meta-analysis	30 empirical studies	Multiple platforms	Academic achievement (Hedges' g = 0.587)	High
Muilwijk et al. (2023)	International	Secondary & Higher Education	Science Education	Meta-analysis	35 comparative studies	Multiple platforms	Conceptual understanding, inquiry learning	High

Study	Country	Educational Level	Discipline	Research Design	Sample	Virtual Laboratory Platform	Primary Outcomes	Quality Assessment
Navarro et al. (2024)	Spain	Undergraduate	Cell Biology	Cross-sectional Survey	Undergraduate students	Labster	Motivation, autonomy, conceptual understanding	Moderate–High
Alnaser (2024)	Saudi Arabia	Undergraduate	Science Education	Structural Equation Modeling	Undergraduate students	Virtual Laboratory System	Self-efficacy, motivation, attitudes toward science	High
Carroll et al. (2025)	Canada	Graduate	Molecular Biology	Educational Intervention	Graduate students	Virtual Molecular Biology Laboratory	Knowledge gain, perceived usefulness	Moderate–High
Peechapol (2021)	Thailand	First-year Undergraduate	Chemistry	Quasi-experimental Study	First-year chemistry students	Virtual Chemistry Laboratory	Academic achievement, self-efficacy	High

The methodological quality of the retained studies was considered adequate for evidence synthesis purposes. All investigations reported clearly defined educational interventions, explicit outcome measures, and sufficient methodological details to permit the extraction of comparable findings. Furthermore, the inclusion of both review-level and primary empirical evidence enabled the synthesis to combine broad cumulative knowledge with context-specific pedagogical observations.

Overall, the retained evidence represented multiple educational systems, instructional designs, disciplinary domains, and learner populations, thereby providing an appropriate empirical basis for examining the pedagogical strengths, limitations, and optimal integration of virtual laboratories into science education.

Overall Evidence Synthesis

Cross-study comparisons revealed consistent educational patterns, despite substantial variations in technological platforms, instructional approaches, and disciplinary contexts. Four recurring pedagogical themes emerged from the evidence. First, virtual laboratories consistently improve students' conceptual understanding by strengthening the connection between theoretical knowledge and laboratory practice. Review-level evidence further indicated that they frequently produced learning outcomes comparable to and occasionally exceeding those of conventional laboratories when conceptual learning was the primary objective. Second, virtual laboratories enhance learners' confidence by reducing uncertainty before physical laboratory participation, particularly among novice students, through repeated exposure to simulated experimental procedures. Third, they generally promoted learning motivation, although these effects were more context-dependent and strongest when simulations were interactive, curriculum-aligned, and supported by instructor guidance. Finally, the evidence consistently suggests that virtual laboratories function most effectively as complements rather than substitutes for physical laboratories, supporting conceptual preparation, procedural familiarization, and repeated low-risk practice, while hands-on laboratories remain essential for developing manual skills and authentic experimental competence. The consistency of these findings across diverse educational systems suggests that the educational value of virtual laboratories depends less on specific technological platforms than on shared pedagogical mechanisms, including visualization, cognitive scaffolding, repeated practice, and enhanced learner confidence (see Table 5).

Table 5.

Cross-Study Synthesis of the Principal Findings.

Educational Outcome	Evidence Consistency	Overall Conclusion
Conceptual Understanding	Very High	Consistently improved
Academic Achievement	High	Moderate positive effect across studies
Self-efficacy	Very High	Strong improvement
Confidence	Very High	Strong improvement
Motivation	Moderate–High	Positive but context dependent
Engagement	High	Improved through interactive simulation
Laboratory Readiness	Very High	Consistently improved
Procedural Skills	Moderate	Improved as preparation rather than replacement
Hands-on Skills	Low	Physical laboratories remain essential

The synthesis further indicated that virtual laboratories generated the strongest educational benefits when integrated within hybrid instructional models. Across nearly all the included studies, the most effective implementation positioned virtual laboratories before physical laboratory sessions, allowing students to develop conceptual understanding and procedural familiarity prior to engaging with real equipment. This sequencing reduces cognitive load during subsequent laboratory work and enables instructors to allocate greater instructional time to higher-order scientific reasoning rather than basic procedural explanations.

Collectively, these findings establish a robust empirical foundation for the subsequent quantitative synthesis, which examines the magnitude and consistency of the reported educational effects across the accepted evidence base.

Quantitative Synthesis

Quantitative evidence consistently supports the positive contribution of virtual laboratories to science learning outcomes. Although methodological heterogeneity precluded the calculation of a single pooled effect size across all the included studies, both review-level and empirical evidence demonstrated substantial convergence in the direction and magnitude of educational effects. The strongest evidence emerged from two meta-analyses conducted. Santos and Prudente (2022) reported an overall standardized mean difference of Hedges' $g = 0.587$, indicating a moderate and educationally meaningful improvement in students' academic achievement after virtual laboratory interventions. Similarly, Muilwijk et al. (2023), synthesizing thirty-five comparative studies, concluded that virtual laboratories produced conceptual learning outcomes broadly comparable to those of traditional laboratory instruction, with differences becoming negligible when conceptual understanding rather than psychomotor performance was the primary instructional objective.

These findings were reinforced by the empirical studies included in this synthesis. Across biology, chemistry, microbiology, and molecular biology education, virtual laboratory interventions consistently improved post-intervention learning outcomes relative to baseline performance, despite differences in assessment instruments and instructional design. For example, Makransky et al. (2016) demonstrated that students who completed virtual simulations achieved laboratory readiness comparable to those who received conventional preparation, while Carroll et al. (2025) reported measurable knowledge gains among approximately 89% of graduate molecular biology students. Comparable improvements in chemistry achievement were also identified by Peechapol (2021), providing further evidence of the robustness of simulation-based instruction across disciplinary contexts.

Quantitative evidence further indicates that the benefits of virtual laboratories extend beyond cognitive achievements. Dyrberg et al. (2017) reported significant improvements in students' confidence when performing laboratory tasks, whereas Navarro et al. (2024) found that 86% of participants perceived increased confidence and 89% reported enhanced conceptual understanding following virtual laboratory activities. Collectively, these findings suggest that virtual laboratories not only improve academic performance but also strengthen learners' confidence and preparedness for subsequent hands-on laboratory experiences.

In cross studies, quantitative indicators converged around three principal educational benefits:

- improved conceptual understanding.
- increased laboratory confidence.
- enhanced academic achievements.

In contrast, the motivational outcomes displayed greater quantitative variability. Although most investigations reported positive effects on learning motivation, the magnitude of improvement varied according to the instructional integration, technological fidelity, learner characteristics, and disciplinary context. Consequently, motivation appears to function as a conditional rather than a universal outcome of virtual laboratory implementation.

Overall, the quantitative evidence suggests that virtual laboratories exert their strongest influence on cognitive learning outcomes and perceived competence, whereas affective outcomes, such as motivation, depend more heavily on instructional design and contextual implementation (Table 6).

Table 6.

Quantitative Evidence Synthesized Across the Included Studies.

Study	Quantitative Indicator	Principal Finding	Interpretation
Santos & Prudente (2022)	Hedges' g = 0.587	Moderate positive effect on achievement	Moderate educational impact
Brinson (2015)	Review of 56 studies	Equal or higher learning outcomes in most studies	Strong support for conceptual learning
Muilwijk et al. (2023)	Meta-analysis (35 studies)	Comparable conceptual learning between physical and virtual investigations	Strong evidence
Carroll et al. (2025)	89% knowledge gain	Significant post-intervention improvement	Strong empirical evidence
Navarro et al. (2024)	≈89% conceptual improvement	Students perceived enhanced understanding	High perceived effectiveness
Navarro et al. (2024)	≈86% confidence improvement	Increased learning confidence	Strong affective outcome
Dyrberg et al. (2017)	Increased laboratory confidence	Positive effect on self-efficacy	Moderate–High evidence
Peechapol (2021)	Significant improvement	Higher achievement and self-efficacy	Strong instructional effect
Makransky et al. (2016)	Comparable laboratory preparation	Equivalent readiness before physical laboratories	Strong preparatory value

The convergence observed across independent quantitative investigations substantially strengthens the confidence in the robustness of the identified learning effects. Despite variations in countries, disciplines, participant populations, and assessment strategies, the overwhelming majority of quantitative findings support the conclusion that virtual laboratories constitute an effective instructional approach for enhancing conceptual learning and laboratory preparedness.

Qualitative Cross-Case Synthesis

While quantitative findings establish the overall effectiveness of virtual laboratories, qualitative evidence provides insights into the pedagogical mechanisms through which these effects emerge. A cross-case comparison of the empirical studies identified four recurring qualitative themes that appeared consistently across different educational contexts.

Theme 1. Virtual laboratories reduce cognitive barriers before practical experimentation

Across biology, chemistry, microbiology, and molecular biology education, students consistently described virtual laboratories as environments that reduced anxiety before entering physical ones. Simulated experimentation enables learners to familiarize themselves with laboratory procedures, equipment, and expected outcomes without fear of making irreversible mistakes. This low-risk environment encourages exploration, repeated practice, and independent learning, thereby facilitating conceptual preparation prior to hands-on experimentation.

Theme 2. Visualization strengthens conceptual understanding

The second recurring theme concerned the visualization of invisible scientific phenomena. Students frequently reported that animations, simulations, and interactive representations enabled them to understand molecular interactions, cellular processes, and experimental mechanisms that are difficult to observe directly in traditional laboratory settings. Rather than replacing practical experimentation, virtual laboratories enhance students' ability to interpret what they observe during physical laboratory activities.

Theme 3. Confidence develops before procedural competence

Qualitative evidence consistently distinguishes between confidence and procedural expertise. Students generally felt more confident after completing virtual laboratory activities because they understood the procedural sequences and laboratory expectations. However, many participants simultaneously acknowledged that genuine procedural competence required interaction with the physical equipment. Thus, confidence appears to precede, rather than replace, hands-on skill acquisition.

Theme 4. Educational value depends on instructional integration

Perhaps the strongest qualitative consensus is the importance of instructional design. Studies consistently emphasize that virtual laboratories are most effective when integrated within broader pedagogical sequences, accompanied by instructor guidance, and explicitly connected to subsequent laboratory activities. Conversely, isolated simulations without pedagogical integration were perceived as less meaningful and produced weaker motivational effects.

These recurring themes appeared across countries despite differences in educational systems, suggesting that the educational effectiveness of virtual laboratories is governed more by instructional integration than by the national or technological context (Table 7).

Table 7.

Cross-Case Qualitative Themes Identified Across the Studies.

Theme	Evidence Across Studies	Educational Interpretation
Reduction of laboratory anxiety	Strong	Facilitates early engagement
Improved conceptual visualization	Very Strong	Supports conceptual understanding
Increased confidence	Very Strong	Enhances laboratory readiness
Safe repetitive practice	Strong	Supports self-directed learning

Theme	Evidence Across Studies	Educational Interpretation
Greater learner autonomy	Moderate–Strong	Encourages independent exploration
Importance of hybrid integration	Very Strong	Maximizes educational effectiveness
Limitation for tactile skills	Very Strong	Physical laboratories remain indispensable
Context-dependent motivation	Moderate	Depends on instructional design

Mechanism Analysis

Beyond documenting the effectiveness of virtual laboratories, cross-national evidence has revealed a coherent explanatory mechanism describing how virtual laboratory environments influence students' learning processes. Rather than acting directly on academic achievement, virtual laboratories appear to operate through a sequence of interconnected psychological and cognitive processes that affect academic achievement. Across the included studies, improvements in learning outcomes consistently emerged through changes in learners' perceptions, cognitive engagement, and confidence, before translating into measurable academic gains.

The synthesis identified four interrelated mechanisms that collectively explain the educational value of virtual laboratories.

Mechanism 1. Cognitive Scaffolding

The first mechanism concerns cognitive scaffolding. Virtual laboratories simplify complex laboratory procedures by decomposing scientific activities into sequential and visually supported tasks. Interactive simulations allow students to repeatedly observe experimental procedures, manipulate variables, and immediately receive feedback without the time pressure that is typically associated with physical laboratory sessions.

Across multiple studies, this structured learning environment reduced unnecessary cognitive load while strengthening the conceptual processing. Rather than expending cognitive resources on equipment operation or procedural uncertainty, students were able to allocate greater attention to understanding the scientific principles, causal relationships, and experimental logic.

Therefore, the evidence suggests that virtual laboratories facilitate conceptual learning primarily through structured cognitive support rather than technological sophistication alone.

Mechanism 2. Psychological Safety and Self-Efficacy Development

A second mechanism has consistently emerged in empirical studies. Virtual laboratories create psychologically safe learning environments in which students can experiment without fear of damaging expensive equipment, wasting laboratory materials, or making irreversible mistakes.

This low-risk environment promotes exploratory behavior, repeated practice, and trial-and-error learning. As learners repeatedly completed the experimental tasks successfully, their confidence gradually increased.

The synthesis indicates that self-efficacy develops through repeated successful interactions with virtual-laboratory environments. Increased confidence subsequently encourages a greater willingness to engage in subsequent physical laboratory activities.

Rather than replacing practical experience, virtual laboratories function as confidence-building environments that psychologically prepare learners for authentic experimentation.

Mechanism 3. Visualization and Conceptual Integration

The third mechanism concerns the scientific visualization.

Many scientific concepts, particularly in biology, chemistry, microbiology, and molecular sciences, are inherently invisible. Molecular interactions, cellular processes, enzyme activity, diffusion mechanisms, and microscopic phenomena cannot be easily observed during conventional laboratory instruction.

Virtual laboratories bridge this limitation by providing dynamic visual representations that connect theoretical explanations to observable experimental outcomes.

Across studies, students have repeatedly reported that visualization enables them to integrate abstract theoretical knowledge with practical laboratory procedures. Instead of memorizing isolated concepts, learners develop coherent mental models that explain why experimental procedures generate particular observations.

Therefore, the evidence indicates that visualization serves as an important mediator linking laboratory activities to conceptual understanding.

Mechanism 4. Hybrid Learning Integration

The final mechanism concerns the integration of instruction. Perhaps the strongest consensus across the evidence base is that virtual laboratories rarely produce optimal educational outcomes when implemented as standalone digital activities. Instead, their effectiveness increased substantially when they were integrated into hybrid instructional sequences (Fig 1).

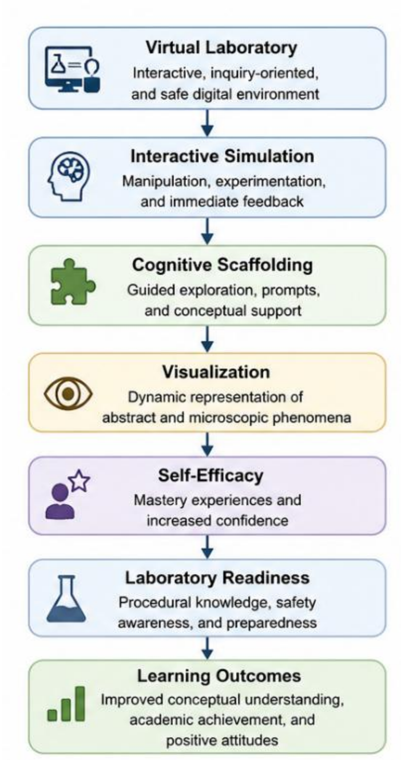

Fig. 1. Mechanism-Based Model of Virtual Laboratory Effectiveness.

The figure illustrates the pedagogical mechanisms through which virtual laboratories contribute to learning outcomes in the field of science education. Interactive simulations provide a cognitively supportive and psychologically safe learning environment that promotes cognitive scaffolding and visualization of scientific phenomena. These processes strengthen learners' self-efficacy and laboratory readiness, ultimately leading to improved conceptual understanding, academic achievement, and overall learning effectiveness. The model synthesizes the recurring mechanisms identified in the included empirical studies, systematic reviews, and meta-analyses.

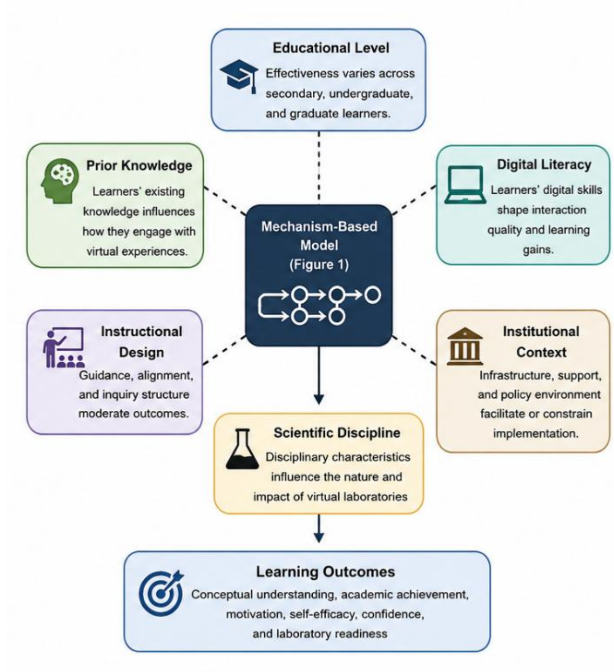

Fig. 2. Boundary Conditions Influencing Virtual Laboratory Effectiveness.

The figure presents the principal boundary conditions identified in the evidence synthesis that moderate the effectiveness of the virtual laboratories. Educational level, prior knowledge, digital literacy, instructional design, institutional context, and scientific discipline influence the extent to which the pedagogical mechanisms shown in Figure 1 translate into improved learning outcomes. These contextual factors do not directly produce learning gains; rather, they strengthen or constrain the mechanisms through which virtual laboratories support conceptual understanding, self-efficacy, laboratory readiness and academic achievement.

This progression enables students to enter physical laboratories with greater conceptual readiness, reduced anxiety, and clearer expectations of experimental procedures.

Consequently, the synthesis supports a hybrid, rather than a substitutional, model of laboratory education. Accordingly, the model based on the effectiveness mechanism of the virtual laboratory is shown in Fig. 2.

Evidence indicates that none of these mechanisms operate independently. Instead, improvements in conceptual understanding, motivation, and confidence reinforce each other throughout the learning process, producing cumulative educational benefits.

Heterogeneity Analysis

Although the overall evidence consistently supports the effectiveness of virtual laboratories, important variations have emerged across learner characteristics, disciplinary contexts, and instructional implementations. Therefore, the synthesis examined potential sources of heterogeneity that may explain the differences in the reported educational outcomes. Educational level was one of the strongest moderators identified across the included studies. Secondary school students and early undergraduate learners generally demonstrated greater improvements in conceptual understanding and self-efficacy than graduate students, which likely reflects differences in prior laboratory experience. Novice learners derive greater benefits from guided simulations because virtual laboratories reduce uncertainty during initial exposure to laboratory practices. In contrast, graduate students, who already possess substantial procedural experience, primarily benefit from conceptual refinement rather than fundamental skill acquisition.

Scientific Discipline

The disciplinary context also influenced the observed educational effects.

The strongest evidence was reported as follows:

- Biology
- Cell Biology
- Microbiology
- Chemistry
- Molecular Biology

These disciplines frequently involve microscopic, hazardous, expensive, or otherwise inaccessible phenomena that are particularly well-suited for digital simulation. Conversely, disciplines requiring extensive manipulation of complex physical equipment showed smaller relative gains from virtual-laboratory instruction.

Instructional Design

Variations in instructional design constituted another important source of heterogeneity. Studies have consistently demonstrated that virtual laboratories produce stronger educational outcomes when they:

- Integrated into existing curricula
- completed before physical laboratory sessions.
- accompanied by instructor feedback
- Connected to assessment activities.
- followed by a reflective discussion.

In contrast, isolated simulation activities produced fewer educational benefits.

Learner Characteristics

Several learner characteristics moderated the effectiveness of virtual laboratories.

Students with:

- lower prior laboratory experience,
- lower initial confidence,
- limited procedural knowledge,

generally exhibited larger improvements than experienced learners did. Similarly, digital literacy influenced students' ability to benefit from simulation-based learning. Learners who experienced fewer technological barriers demonstrated greater engagement and stronger learning outcomes.

Institutional Context

Cross-national comparisons revealed surprisingly limited variations between countries. Although institutions differed substantially in terms of technological infrastructure, curriculum design, and available laboratory resources, the overall direction of educational effects remained remarkably stable. This finding suggests that pedagogical principles, rather than the national context alone, play a dominant role in determining virtual laboratory effectiveness (Table 8).

Table 8.

Sources of Heterogeneity Across Included Studies.

Moderator	Overall Influence	Evidence Strength	Interpretation
Educational level	High	Strong	Larger effects among novice learners
Prior laboratory experience	High	Strong	Greater benefits for inexperienced students
Scientific discipline	Moderate	Strong	Highest effects in biology and chemistry
Digital literacy	Moderate	Moderate	Influences learner engagement
Instructional integration	Very High	Very Strong	Critical determinant of effectiveness
Simulation fidelity	Moderate	Moderate	Improves realism but not necessarily learning
Institutional resources	Low–Moderate	Moderate	Affect implementation quality
National context	Low	Moderate	Similar mechanisms observed across countries

The heterogeneity analysis demonstrated that the effectiveness of virtual laboratories is neither universal nor context-free. Rather, educational outcomes emerge through the interaction of learner characteristics, instructional design, disciplinary requirements and institutional implementation. Nevertheless, despite these contextual variations, the evidence consistently supports a common pedagogical principle: virtual laboratories are most effective when embedded within carefully designed hybrid learning environments that combine conceptual preparation with authentic, hands-on experimentation.

Robustness Analysis

To assess the robustness of the synthesized evidence, the retained studies were examined across multiple dimensions, including methodological design, educational level, disciplinary context, intervention characteristics, and the consistency of reported outcomes. By integrating evidence from systematic reviews, meta-analyses, quasi-experimental studies, controlled interventions, and perception-based investigations, the synthesis employed methodological triangulation to reduce the reliance on any single research design and strengthen the credibility of the overall conclusions.

Overall, the evidence demonstrates a high degree of consistency. Although the magnitude of educational gains varied across studies, all empirical investigations reported positive effects in at least one major outcome domain, including conceptual understanding, academic achievement, motivation, self-efficacy, confidence, and laboratory readiness. The strongest convergence was observed for conceptual understanding and self-efficacy, which were consistently supported by both review-level and primary evidence. In contrast, motivational outcomes showed greater variability, with stronger effects reported when virtual laboratories were embedded within interactive, instructor-supported learning environments rather than implemented as standalone activities.

The robustness of the findings was further supported by the educational level and research design. While undergraduate students generally exhibited greater improvements than graduate learners, the direction of the educational effects remained stable across all contexts. Likewise, meta-analytic findings closely aligned with those reported in individual empirical studies, indicating that the observed benefits were not artifacts of particular methodological approaches but reflected broader pedagogical trends.

Finally, the synthesis suggests that educational effectiveness depends more on pedagogical integration than on technological sophistication. High-fidelity immersive simulations did not consistently outperform desktop-based virtual laboratories when the instructional design, curriculum alignment, and feedback mechanisms were comparable. This finding highlights instructional design, rather than technological complexity, as the principal determinant of effective virtual-laboratory implementation. Collectively, these robustness checks demonstrate that the central conclusions of the present synthesis remain stable across diverse methodological approaches, learner populations, disciplinary domains and educational settings (Table 9).

Table 9.

Robustness Assessment of Evidence Synthesis.

Dimension	Evidence	Overall Assessment
Methodological diversity	Review, meta-analysis, quasi-experimental, mixed-methods	High robustness
Cross-disciplinary consistency	Biology, Chemistry, Microbiology, Molecular Biology	High robustness
Educational level	Secondary, Undergraduate, Graduate	Stable direction of effects
Geographical diversity	Europe, North America, South America, Asia, Middle East	Strong external validity
Consistency of conceptual learning outcomes	Very high	Robust finding
Consistency of self-efficacy outcomes	Very high	Robust finding

Dimension	Evidence	Overall Assessment
Consistency of motivational outcomes	Moderate	Context dependent
Procedural laboratory skills	Moderate	Complementary rather than substitutive
Overall confidence in evidence	High	Strong evidence supporting hybrid laboratory instruction

The present evidence synthesis integrates findings from nine complementary investigations conducted across diverse educational systems, disciplines, and methodological traditions. Despite variations in instructional design, learner characteristics, and technological platforms, the evidence converged on a consistent conclusion regarding the educational value of virtual laboratories.

Across the included studies, the strongest and most consistent finding was improvement in conceptual understanding, with students achieving learning outcomes comparable to, and in some cases exceeding, those of conventional laboratory instruction. Quantitative evidence further demonstrated moderate but educationally meaningful gains in academic achievement, supporting the pedagogical effectiveness of virtual-laboratory instruction. The synthesis also consistently identified improvements in self-efficacy and laboratory confidence, indicating that virtual laboratories enhance learners' preparedness for subsequent hands-on experimentation rather than replacing procedural competence. Although learning motivation generally improved, its effects were more context-dependent and strongest when virtual laboratories were integrated into well-designed instructional sequences.

Perhaps the most significant finding concerns the pedagogical role of virtual laboratories. None of the included studies supported the replacement of physical laboratories with virtual environments. Instead, the evidence consistently favors hybrid laboratory models, in which virtual laboratories support conceptual preparation, confidence building, and repeated low-risk practice, while physical laboratories remain essential for developing procedural skills and authentic scientific inquiry.

Collectively, these findings support a mechanism-based interpretation of the effectiveness of virtual laboratories. Educational benefits arise not from digital technology itself but from the pedagogical opportunities created through visualization, cognitive scaffolding, repeated practice, immediate feedback, and psychologically safe learning environments. These mechanisms strengthen conceptual understanding and learner confidence, thereby promoting more effective engagement in subsequent lab activities.

Overall, the synthesis indicates that the most evidence-based instructional approach is the pedagogical integration of virtual and physical laboratories rather than technological substitution alone. Such hybrid laboratory ecosystems maximize conceptual learning, improve laboratory readiness, strengthen learner confidence, and preserve the distinctive educational value of authentic experimental practices.

4. Discussion

The present cross-national evidence synthesis demonstrates a consistent pattern across the included studies: virtual laboratories enhance conceptual understanding, strengthen self-efficacy, improve laboratory readiness, and support meaningful academic achievement. Although the magnitude of these effects varies across educational contexts, learner characteristics, and instructional implementations, the direction of the evidence remains remarkably consistent. Rather than functioning as isolated outcomes, conceptual learning, motivation, and confidence emerge as interrelated dimensions of the learning process, collectively shaping students' engagement with scientific inquiry.

These findings support contemporary perspectives on simulation-based learning, which propose that technology contributes to learning not only through digital representation but also through the pedagogical affordances it creates. Across the included studies, virtual laboratories consistently reduced barriers associated with unfamiliar laboratory environments by providing opportunities for repeated practice, immediate feedback, and the visualization of abstract scientific phenomena. These characteristics appear to facilitate cognitive scaffolding while simultaneously strengthening learners' confidence before engaging in physical laboratory activities.

Theoretical Implications

These findings contribute to three complementary areas of theory development. First, they extended simulation-based learning theory by clarifying that the educational value of virtual laboratories lies primarily in supporting conceptual preparation rather than reproducing physical experimentation. Second, they reinforce theoretical models linking self-efficacy, motivation, and learning achievement by demonstrating that these constructs develop interactively in digitally supported laboratory environments. Third, they strengthen hybrid laboratory frameworks by demonstrating that virtual and physical laboratories perform complementary rather than competing educational functions.

Importantly, the evidence suggests that virtual laboratories should not be evaluated based on the extent to which they imitate physical laboratories. Instead, their educational value derives from providing structured opportunities for visualization, conceptual exploration, repeated experimentation and psychologically safe learning experiences. These mechanisms explain why conceptual understanding and self-efficacy consistently emerge as the strongest outcomes in diverse educational contexts.

Interpretation of the Mechanisms

The mechanism of synthesis presented in Figure 1 provides a coherent explanation for the observed learning outcomes. Interactive simulations first create a cognitively supportive environment that facilitates visualization and conceptual organization. These experiences strengthen learners' self-efficacy and laboratory readiness, which subsequently promote a deeper conceptual understanding and improved academic performance. Rather than representing independent effects, these processes operate as an integrated pedagogical pathway linking digital learning environments to meaningful educational outcomes.

The findings further indicate that the effectiveness of this mechanism is influenced by several contextual factors. As summarized in Fig. 2, the educational level, prior knowledge, digital literacy, instructional design, institutional context, and scientific discipline moderate the extent to which virtual labs support learning. These factors do not independently determine educational outcomes but influence the strength and consistency of the pedagogical mechanisms identified in the synthesized evidence.

Practical Implications

This evidence has several implications for educational practice and policy. At the instructional level, virtual laboratories should be implemented primarily as preparatory or complementary learning environments, rather than as replacements for physical laboratories. Providing students with opportunities to explore scientific concepts through interactive simulations before conducting hands-on experimentation appears to maximize both conceptual understanding and laboratory confidence.

At the institutional level, effective implementation requires investment in both technological infrastructure and instructional design and faculty development. Therefore, educational policies should emphasize pedagogically integrated hybrid laboratory models that combine the conceptual advantages of virtual laboratories with the procedural and experiential strengths of physical experimentation.

Limitations and Future Research

This study has several limitations. The included studies differed considerably in terms of research design, outcome measures, instructional implementation, and educational context, limiting direct quantitative comparisons across investigations. In addition, most studies have examined relatively short-term educational interventions, leaving the long-term development of conceptual understanding and self-efficacy insufficiently explored.

Future research should therefore examine the long-term educational impact of virtual laboratories through longitudinal investigations, explore the cognitive mechanisms underlying simulation-based learning using process-oriented methodologies, and evaluate the effectiveness of hybrid laboratory models in diverse institutional and disciplinary contexts. Comparative research examining how digital infrastructure, instructional design, and learner characteristics jointly influence virtual laboratory effectiveness would further strengthen the evidence base for future educational policies and practices.

5. Conclusions

At its core, this study demonstrates that virtual laboratories enrich science learning not by replicating physical laboratory experiences but by reshaping the cognitive and motivational conditions under which students engage with scientific concepts. This finding directly addresses the central question raised in the Introduction: digital environments contribute meaningfully to experimental learning when they are positioned as pedagogically complementary, rather than technological substitutes, for physical laboratories.

The synthesis integrates dispersed empirical evidence into a coherent explanation of how structured virtual experimentation promotes conceptual understanding, strengthens self-efficacy, and supports learning motivation. This study extends simulation-based learning theory by showing that educational benefits emerge through pedagogical mechanisms—particularly visualization, cognitive scaffolding, repeated low-risk practice, and immediate feedback—rather than through technological sophistication alone (Makransky & Mayer, 2022; Chi & Wylie, 2014). The findings also refine hybrid learning frameworks by reinforcing the complementary roles of virtual and physical laboratories, with the former supporting conceptual preparation and confidence building, and the latter remaining indispensable for procedural competence and authentic experimentation (Budnyk et al., 2025).

More broadly, this study contributes to an emerging mechanism-oriented perspective in digital science education. Instead of framing virtual laboratories as equivalents to physical laboratories, the evidence suggests that they should be understood as environments that reorganize learners' cognitive engagement with scientific knowledge. Across the nine countries represented in this synthesis, the identified mechanism—structured, low-risk experimentation that enhances learner control, confidence, and conceptual integration— was remarkably consistent, although its strength varied according to contextual factors such as digital literacy, prior laboratory experience, instructional sequencing, and institutional readiness. This mechanism-oriented perspective may also inform future research in related domains, including medical simulation, engineering education, and vocational training, where similar interactions between technology, cognition, and learner behavior are increasingly observed (Bond et al., 2021; Kim & Burić, 2020).

These findings have important practical implications. For instructors, virtual laboratories are most effective when implemented as preparatory or complementary learning environments before hands-on experimentation. For higher education institutions, investment should prioritize pedagogically integrated hybrid laboratory models rather than technological sophistication alone, as mid-fidelity simulations can provide substantial educational benefits when supported by an appropriate instructional design. At the policy level, virtual laboratories represent a practical strategy for expanding equitable access to laboratory education, particularly in settings where financial, geographical, or infrastructural constraints limit opportunities for conventional laboratory instruction to be conducted.

Nevertheless, the conclusions of this synthesis should be interpreted within the scope of its conditions. The educational advantages of virtual laboratories are most evident during conceptual preparation, confidence building, and early stage laboratory learning, whereas advanced procedural skills and authentic experimental competence continue to depend on physical laboratory experience (Vermylen et al., 2025). Furthermore, because the synthesis draws upon secondary evidence encompassing diverse research designs, instructional implementations, and outcome measures, direct quantitative comparability across studies is limited. Future research should therefore examine the long-term development of conceptual understanding and self-efficacy through longitudinal investigations, explore the cognitive processes underlying simulation-based learning using process-oriented methodologies, and evaluate hybrid laboratory models across diverse institutional and policy contexts. Mixed-method research integrating quantitative modeling with qualitative investigation would further strengthen the understanding of the pedagogical mechanisms identified in this synthesis.

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Conflicts of interest

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Authors contribution statement

Ehsan Abbaspour: Conceptualization; Methodology; Investigation; Supervision; Project administration; Validation; Writing – original draft; Writing – review & editing. Sarmad Hamza Jassim: Methodology; Data curation; Formal analysis; Validation; Visualization; Writing – original draft; Writing – review & editing. Bushra Jawad M.Ridha: Data curation; Investigation; Resources; Visualization; Writing – review & editing.

All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available because they contain information that could compromise the privacy and confidentiality of the research participants.

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