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# Virtual Laboratories for Equitable STEM Learning in Resource-Constrained Education: A Systematic Review

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## Abstract

Virtual laboratories are increasingly used to extend practical science, technology, engineering, and mathematics (STEM) learning where equipment, consumables, safety, staffing, or access to physical laboratories are constrained. This systematic narrative review examines how virtual laboratories support STEM learning and under which technological, pedagogical, and institutional conditions their benefits may extend to resource-constrained educational settings. A structured search of Scopus, Web of Science, and Google Scholar was conducted for literature published from 2010 to 2024, with citation verification and a targeted update during revision. The screening record identified 320 records; after duplicate removal and screening, 30 studies were retained for the core synthesis. Findings show that virtual laboratories can produce conceptual-learning outcomes comparable to physical laboratories and can strengthen engagement, self-efficacy, visualization, and opportunities for repeated practice. However, effects are conditional. Sequential or blended use of virtual and physical laboratories is frequently stronger than treating either mode as a universal substitute, and immersive virtual reality can increase presence while also increasing cognitive load. Access to a virtual laboratory should therefore not be equated with educational equity: devices, connectivity, reliable power, teacher capability, curriculum alignment, accessibility, and instructional guidance determine who benefits. The review proposes an affordance-and-conditions framework in which virtual laboratories are positioned as complementary infrastructure for resilient STEM education, particularly when designed for low-bandwidth or offline use and integrated with teacher-supported inquiry and authentic practical experiences.

**Keywords:** Virtual laboratories; STEM education; resource-constrained education; educational equity; simulation-based learning; blended laboratories

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## INTRODUCTION

Laboratory activity occupies a distinctive place in STEM education because it connects abstract models with observation, measurement, manipulation, uncertainty, and evidence-based reasoning. Yet laboratory provision is uneven. Capital costs, consumables, maintenance, safety requirements, large enrolments, specialist staffing, unreliable electricity, and limited access to equipment can reduce the frequency and quality of practical work. These constraints are particularly visible in under-resourced institutions, but they are not confined to low-income countries: distance education, rapid enrolment growth, safety restrictions, and temporary disruptions can also limit laboratory access in otherwise well-resourced systems (de Jong et al., 2013; Faulconer & Gruss, 2018; Potkonjak et al., 2016).

Virtual laboratories offer one response to this problem. In this review, a virtual laboratory is understood as a computer-mediated environment in which learners perform or rehearse an experiment by manipulating variables, apparatus, procedures, or data in a way that represents a laboratory task. This definition is narrower than the broad

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category of educational simulation. It also distinguishes virtual laboratories from remote laboratories, where students control real physical equipment through a network, and from immersive virtual reality (VR), which is a display and interaction modality that may or may not reproduce an authentic laboratory workflow. These distinctions matter because different technologies create different learning affordances and impose different infrastructure requirements (Heradio et al., 2016; Potkonjak et al., 2016).

The early literature often framed the issue as a competition between 'virtual' and 'real' laboratories. More recent evidence suggests that this binary is unhelpful. Reviews and comparative studies show that virtual environments can match or exceed hands-on environments on some measures, especially conceptual knowledge, while physical laboratories retain advantages for tactile coordination, equipment handling, dealing with noisy real data, and embodied procedural experience. Sequential or blended designs can exploit the strengths of both (Brinson, 2015; Kapici et al., 2019; Olympiou & Zacharia, 2012). The relevant question is therefore not whether virtual laboratories are intrinsically better, but which form of laboratory experience is appropriate for a specific learning objective, learner group, and implementation context.

This distinction is especially important for educational equity. A digital resource can expand nominal access while simultaneously creating new exclusions if learners lack devices, electricity, connectivity, accessible interfaces, teacher support, or sufficient time to engage with the activity. Equity also concerns the quality of the learning opportunity, not merely the presence of a login or software package. A virtual laboratory that is technically available but poorly aligned with curriculum or difficult to use may widen rather than reduce differences between learners. The present review therefore treats access, learning outcomes, and implementation conditions as analytically connected rather than separate topics (International Commission on the Futures of Education, 2021).

The review has four objectives: (1) to synthesize evidence on the effects of virtual laboratories on learning and engagement across STEM disciplines; (2) to examine how virtual laboratories may expand or constrain equitable access to practical learning; (3) to identify technological, pedagogical, and institutional conditions that explain variation in outcomes; and (4) to derive implementation principles for resource-constrained education. Its distinctive contribution is an integrated framework linking laboratory affordances, learning mechanisms, infrastructure and teacher conditions, and educational outcomes. Unlike reviews primarily concerned with technological modalities or aggregated learning outcomes, the present synthesis explicitly examines how pedagogical mechanisms and implementation conditions interact to shape opportunities for meaningful and equitable STEM learning. Its contribution is an integrated analytical framework rather than a claim of newly established causal relationships.

## LITERATURE REVIEW AND ANALYTICAL FRAMEWORK

### Defining the modality

Terminology in the field is inconsistent. Virtual laboratories may range from browser-based 2D simulations to realistic 3D environments. Immersive VR typically adds head-mounted displays and embodied interaction; remote laboratories provide digital access to real equipment; general simulations may model a scientific concept without reproducing laboratory procedures. Conflating these categories can obscure why studies differ. For example, a low-bandwidth virtual circuit may be suitable for repeated conceptual inquiry on ordinary computers, whereas immersive VR can demand expensive hardware and may introduce additional cognitive load. A remote laboratory provides real data and equipment behavior but depends on networked physical infrastructure. The revised synthesis therefore interprets results in relation to modality, rather than treating all digital practical work as one intervention (Heradio et al., 2016; Potkonjak et al., 2016).

## Learning outcomes and the case for complementarity

Across science and engineering, virtual laboratories have repeatedly shown potential to support conceptual understanding. Brinson's (2015) review found that measured outcomes in virtual and remote laboratories were often equal to or higher than those in hands-on conditions, although the evidence base disproportionately assessed knowledge and understanding. Comparative studies in physics and chemistry similarly report cases of comparable performance (Darrah et al., 2014; Hawkins & Phelps, 2013; Zacharia & Olympiou, 2011). These findings justify virtual laboratories as legitimate learning environments, but they do not demonstrate that physical laboratories are unnecessary.

A stronger pattern is complementarity. Olympiou and Zacharia (2012) found that a deliberately blended sequence of physical and virtual manipulatives improved conceptual understanding more than either mode alone in their light-and-color study. Kapici et al. (2019) likewise reported better knowledge and inquiry-skill outcomes when middle-school learners used hands-on and virtual laboratories sequentially rather than in isolation. In chemistry, Bortnik et al. (2017) positioned a virtual component as pre-laboratory preparation and reported improvements in research practices. These studies suggest a design principle: use virtual laboratories where their affordances - safe repetition, visibility of hidden processes, rapid feedback, reset capability, and flexible access - add value, while retaining physical experience where tactile, measurement, troubleshooting, or equipment-handling skills are learning objectives.

## Engagement, immersion, and cognitive load

Virtual environments can be engaging, but engagement should not be treated as a proxy for learning. Bonde et al. (2014) demonstrated the motivational potential of gamified laboratory simulation, and several studies report positive learner perceptions, self-efficacy, or interest. Yet Makransky et al. (2019a) provides an important counterexample: university students using an immersive VR version of a science simulation reported substantially greater presence but learned less and experienced higher cognitive load than students using the desktop version. This finding is theoretically important because it shows that realism or immersion can add seductive detail, and processing demands that compete with learning.

Cognitive-load theory therefore provides a useful explanatory lens. A well-designed simulation can reduce extraneous load by highlighting relevant variables, pacing steps, and visualizing invisible mechanisms; poorly designed or highly immersive environments can add interface demands that consume working-memory resources. The implication is not that immersive VR is undesirable, but that the level of technological sophistication should follow the learning objective rather than drive it.

## Equity and resource-constrained education

Virtual laboratories can reduce dependence on scarce consumables, increase repeatability, support distance participation, and make some dangerous or expensive experiments available to more learners. They may also help institutions schedule practical activities around limited physical facilities. These are genuine access advantages. However, equity requires more than distribution of software. Learners need suitable devices, dependable power, accessible interfaces, sufficient digital literacy, and instructional support. Teachers need time and professional learning to connect virtual tasks to disciplinary goals, facilitate inquiry, interpret learner data, and decide when physical follow-up is essential.

Recent evidence from rural South African science teachers reinforces the importance of implementation conditions: teachers reported generally positive perceptions of virtual laboratories, while the study situates adoption within the realities of under-resourced rural schooling and teacher acceptance (Shambare & Jita, 2025).

For resource-constrained settings, design choices are therefore central to equity. Offline-capable or local-network deployment, modest hardware requirements, small installation sizes, shared-device workflows, downloadable teacher guides, and low-bandwidth synchronization can be more consequential than advanced graphics. Virtual laboratories should also be mapped to the local curriculum and assessed using the same learning objectives applied to other practical work. The equity question becomes: does the intervention reduce constraints on meaningful participation without transferring the burden to connectivity, devices, or unsupported teachers?

## Theoretical framework

This review integrates constructivist, experiential-learning, and cognitive-load perspectives as mechanisms rather than treating them as background theories. Constructivism explains why interactive manipulation, prediction, feedback, and revision can support knowledge construction. Experiential learning draws attention to a cycle of action, observation, reflection, conceptualization, and transfer; a virtual activity is educationally stronger when learners interpret outcomes and connect them to authentic practice rather than merely follow screen prompts. Cognitive-load theory explains why scaffolds and visualizations can aid learning while unnecessary immersion, interface complexity, or split attention can impair it.

Figure 1 combines these mechanisms with implementation conditions. The same virtual-laboratory affordance can lead to different outcomes depending on teacher guidance, learner prior knowledge, device and power access, curriculum fit, and whether the modality is appropriate for the intended skill. This framework guides the synthesis that follows.

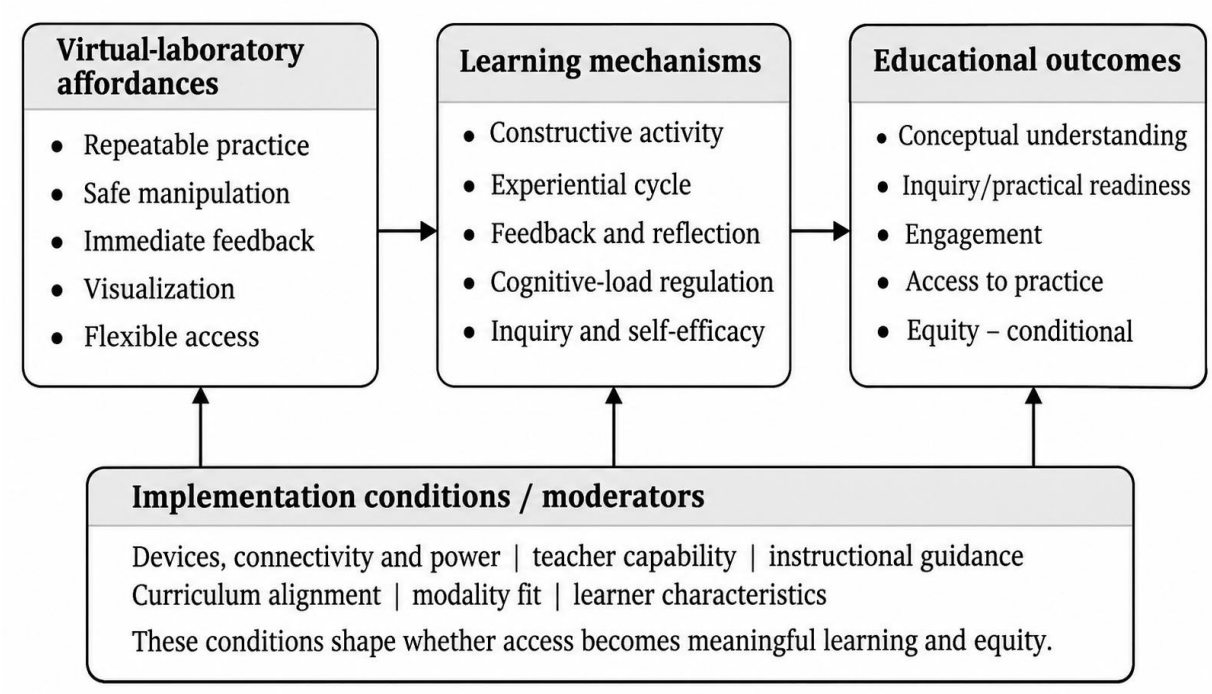



Figure 1. Analytical framework linking virtual-laboratory affordances, learning mechanisms, implementation conditions, and outcomes.

## RESEARCH METHOD

### Review design and reporting

This study is a systematic narrative review of virtual-laboratory evidence in STEM education. The design was selected because the literature contains heterogeneous interventions, disciplines, age groups, outcome measures, and research designs that are not suitable for a single pooled effect estimate. Study identification, screening, eligibility, and inclusion are presented using a PRISMA 2020-informed flow structure (Page et al., 2021). Because the original search record is incomplete, the review does not claim full compliance with all PRISMA 2020 reporting requirements. The synthesis comprises 30 core sources, with the search strategy, eligibility criteria, quality appraisal approach, and synthesis procedures described below. Limitations in the completeness of the original search documentation are explicitly acknowledged.

### Information sources, dates, and search strategy

The original review searched Scopus, Web of Science, and Google Scholar for records published from January 2010 through December 2024. The exact date of the initial database search was not preserved in the submitted review record and is therefore not reconstructed retrospectively. During revision on 14 September 2026, citation metadata and DOI links were verified, and a targeted literature update was undertaken to identify recent evidence useful for interpretation; post-2024 items were used only to contextualize the discussion and were not added to the 30-source core synthesis.

The main Boolean concept structure was: ("virtual laborator*" OR "virtual lab*" OR "remote laborator*" OR "laboratory simulation*") AND (STEM OR science OR technolog* OR engineer* OR mathematics) AND (learn* OR teach* OR education) AND (achievement OR "learning outcome*" OR engagement OR "conceptual understanding" OR inquiry OR skill* OR equity OR access* OR "resource-constrained" OR rural). In Scopus this logic was applied to TITLE-ABS-KEY fields; in Web of Science, it was applied as a Topic search (TS); Google Scholar was searched using shortened phrase combinations because it does not support the full database syntax consistently. Backward reference checking of high-relevance reviews was used to locate comparative studies.

### Eligibility criteria

Studies were eligible when they: (a) addressed STEM education; (b) involved a virtual, simulated, remote, or digitally mediated laboratory experience with an experimental or practical-learning component; (c) reported empirical learning, skill, engagement, self-efficacy, access, or implementation findings, or synthesized empirical laboratory studies; (d) were published in English; and (e) fell within the 2010-2024 publication window for the core synthesis. Studies were excluded when they concerned generic e-learning without laboratory activity, used VR solely for visualization with no practical task, focused on non-STEM professional training, lacked a clear method, duplicated another report, or provided only promotional/technical descriptions without educational evidence. Policy reports were used to frame equity and implementation but were not counted in the 30-source core.

### Screening and selection

The submitted screening record reported 320 identified records. After removal of 60 duplicates, 260 titles and abstracts were screened; 180 records were excluded as outside the eligibility criteria. Eighty full texts were assessed, 50 were excluded, and 30 sources were retained for the core synthesis (Figure 2). The original screening record did not preserve the exact initial search date, database-specific hit counts, or itemized reasons for each full-

text exclusion. The revised manuscript therefore reports the available totals without reconstructing unrecorded details; this reporting limitation is acknowledged explicitly rather than inventing retrospective counts.

## Data extraction and quality appraisal

For each included source, the revision extracted discipline, educational level or setting where reported, laboratory modality, comparison or study type, primary learning or implementation finding, and conditions relevant to interpretation. Empirical studies were appraised using design-appropriate principles from the Mixed Methods Appraisal Tool (MMAT), including clarity of research questions, appropriateness of sampling and comparison, completeness and validity of outcome measurement, coherence between data and interpretation, and integration of qualitative and quantitative components where relevant (Hong et al., 2018). Review papers were examined for transparent search/selection procedures and the alignment between included evidence and conclusions.

A single numerical quality score was not assigned because MMAT guidance favors criterion-level interpretation over indiscriminate aggregation. Methodological limitations were considered when interpreting the strength and transferability of findings, although a reproducible study-level weighting procedure was not available. The appraisal informed the interpretation of evidence across study designs rather than producing a numerical ranking of individual studies. Table 3 summarizes the recurring methodological considerations identified in the literature and should not be interpreted as a study-level MMAT assessment or a formal risk-of-bias classification for each included source. Recurring concerns in this literature include convenience samples, short interventions, heavy reliance on self-report, heterogeneous definitions of 'virtual laboratory,' and under-measurement of tactile or procedural skills compared with conceptual knowledge (Brinson, 2015; Faulconer & Gruss, 2018; Chan et al., 2021).

## Synthesis

Because outcome measures and intervention forms were heterogeneous, statistical pooling was not attempted in this review. Evidence was synthesized thematically across five linked domains: (1) conceptual learning and achievement; (2) inquiry, practical readiness, and transfer; (3) engagement, motivation, and self-efficacy; (4) access and equity; and (5) technological, pedagogical, and institutional implementation conditions. Contradictory and conditional findings were retained rather than resolved into an advocacy conclusion. Particular attention was given to whether studies treated virtual laboratories as replacements, supplements, or components of blended/sequential laboratory design.

Table 1. Search, eligibility, appraisal, and synthesis framework.

| Component | Revised specification |
|---|---|
| Databases | Scopus, Web of Science, Google Scholar; backward reference checking of high-relevance reviews. |
| Core publication window | January 2010-December 2024. |
| Search date and revision update | Initial database-search date not preserved in the submitted record; citation verification / targeted contextual update: 14 September 2026. |
| Core concepts | Virtual/remote laboratory; laboratory simulation; STEM/science/technology/engineering/mathematics; learning/teaching/education; achievement, engagement, conceptual understanding, inquiry, skills, equity, access. |
| Inclusion | English-language empirical or evidence-synthesis studies with a laboratory/practical-learning component and reported educational or implementation outcomes. |

| Component | Revised specification |
|---|---|
| Exclusion | Generic e-learning without laboratory activity; VR visualization without practical task; non-STEM training; unclear method; duplicate report; promotional/technical description without educational evidence. |
| Quality appraisal | Design-appropriate MMAT principles for empirical work; transparency and evidence-conclusion alignment for reviews. |
| Synthesis | Thematic systematic narrative synthesis; no pooled meta-analysis because modalities, outcomes and designs were heterogeneous. |

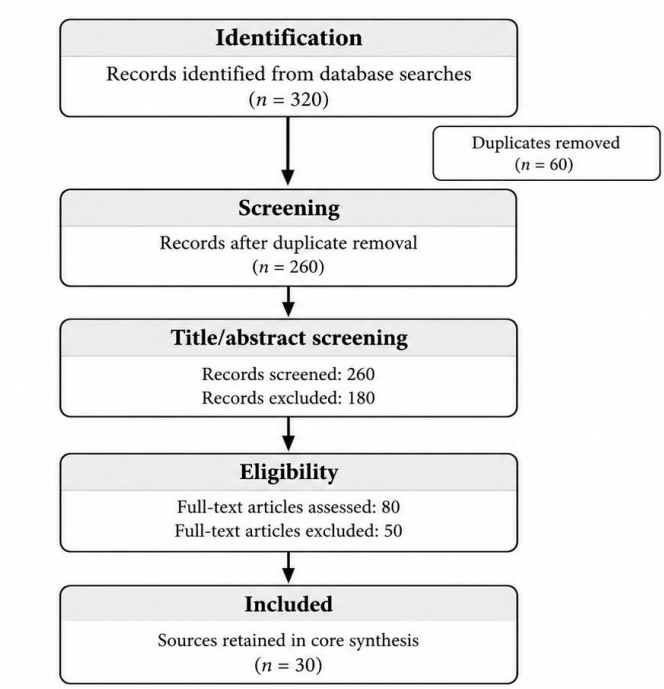



Figure 2. Study-selection flow. Counts are retained from the submitted manuscript's screening record.

## FINDINGS AND DISCUSSION

### Overview and cross-study pattern

The 30-source core spans physics, chemistry, biology/biotechnology, engineering, and cross-disciplinary STEM syntheses. It includes comparative experiments, quasi-experiments, mixed-methods evaluations, and evidence reviews. Across the reviewed evidence, virtual laboratories demonstrate potential to support conceptual learning and practical preparation, particularly when instructional design aligns with intended outcomes. However, the heterogeneity of study designs, outcome measures, and educational contexts prevents a general conclusion that virtual laboratories consistently outperform physical laboratories. Table 2 summarizes the 30 sources included in the core synthesis. Additional studies cited in the discussion are used to contextualize or extend the interpretation of these findings and are not included in the core synthesis unless explicitly identified in the table.

Across literature, conceptual knowledge is the most frequently measured outcome. This creates an important evidence asymmetry: the claim that virtual laboratories can support conceptual learning is stronger than the claim that they can replace physical laboratories for manual technique, equipment troubleshooting, sensory judgment, measurement uncertainty, teamwork around real apparatus, and safety practice. Brinson (2015) and Faulconer and Gruss (2018) explicitly identify this imbalance, and the chemistry review by Chan et al. (2021) similar notes limited skill-based evidence.

Table 2. Cross-study synthesis of the 30 verified sources used in the revised analysis.

| Source | Context | Modality / design | Main findings or condition |
|---|---|---|---|
| Rutten et al. (2012) | Science; review | Computer simulations | Benefits depend on instructional support; simulations can enhance rather than simply replace instruction. |
| Smetana & Bell (2012) | Science; critical review | Computer simulations | Positive effects are strongest when simulations are embedded in purposeful pedagogy and guidance. |
| Zacharia & Olympiou (2011) | University physics | Physical/virtual manipulation | Virtual and physical manipulation produced comparable conceptual gains under controlled instruction. |
| Olympiou & Zacharia (2012) | University physics | Blended physical + virtual | Purposeful blending outperformed either physical or virtual manipulation alone for conceptual understanding. |
| Pyatt & Sims (2012) | School science | Virtual vs physical inquiry | Both modes supported inquiry; access and learner attitudes varied with format. |
| de Jong et al. (2013) | Science/engineering; review | Physical + virtual labs | Argues for complementary use based on the distinctive affordances of each environment. |
| Hawkins & Phelps (2013) | University chemistry | Virtual vs hands-on electrochemistry | No overall significant difference in pre/post or setup performance; some item-level differences occurred. |
| Tatli & Ayas (2013) | Chemistry | Virtual chemistry lab | Virtual use supported achievement and equipment recognition; findings favor guided use rather than universal replacement. |
| Donnelly et al. (2013) | Chemistry | Virtual inquiry lab | Virtual inquiry made experimentation processes more visible and supported structured scientific inquiry. |
| Merchant et al. (2014) | K-12/higher education; meta-analysis | VR-based instruction | Overall positive learning effects, with design features and instructional context moderating outcomes. |
| Darrah et al. (2014) | University physics | Virtual vs hands-on | Virtual labs were comparable to hands-on labs for measured learning in the studied introductory contexts. |
| Bonde et al. (2014) | Biotechnology | Gamified simulation | Simulation supported motivation and learning, illustrating the value of repeated, low-risk practice. |
| Brinson (2015) | STEM; empirical review | Virtual/remote vs hands-on | Most comparisons reported equal or higher measured outcomes in non-traditional labs, but knowledge outcomes were overrepresented. |
| Potkonjak et al. (2016) | Science/technology/engineering; review | Virtual laboratories | Maps technological approaches and stresses the need to evaluate pedagogy, realism, interaction and scalability together. |

| Source | Context | Modality / design | Main findings or condition |
|---|---|---|---|
| Heradio et al. (2016) | STEM; bibliometric review | Virtual/remote labs | Shows sustained growth and diversification of virtual/remote laboratory research across disciplines. |
| Bortnik et al. (2017) | University analytical chemistry | Virtual pre-lab + hands-on | Blended preparation improved research practices and scientific-literacy-related performance. |
| Faulconer & Gruss (2018) | Science; narrative review | Online/remote/ distance labs | Learning can be comparable, but evidence on procedural skill, cost and later hands-on readiness remains incomplete. |
| Kapici et al. (2019) | Middle-school science | Hands-on/virtual/sequential | Sequential use produced better knowledge and inquiry-skill outcomes than isolated use. |
| Makransky et al. (2019a) | University science simulation | Immersive VR vs desktop | Immersive VR increased presence but produced less learning and higher cognitive load in the tested design. |
| Makransky et al. (2020) | Science | Immersive VR simulation | Immersion can stimulate interest and aspirations, but motivational outcomes should not be treated as equivalent to learning. |
| Kolil et al. (2020) | Chemistry; multi-institution | Virtual platform | Virtual preparation can strengthen experimental self-efficacy and reduce anxiety before physical laboratory work. |
| Paxinou et al. (2020) | University biology | 3D VR microscopy | VR supported conceptual learning and transfer to microscope-related performance in the studied setting. |
| Agbonifo et al. (2020) | Secondary/undergraduate chemistry | VR titration platform | Students reported usability and perceived learning value; useful primarily as preparatory practice. |
| Cano de las Heras et al. (2021) | Chemical/biochemical engineering | Virtual fermentation lab | Students valued flexibility and time efficiency; authors recommend supplement/preparation rather than unqualified replacement. |
| Peechapol (2021) | Undergraduate chemistry | Virtual laboratory simulation | Reported gains in achievement/self-efficacy when simulation supplemented conventional instruction. |
| Chan et al. (2021) | Chemistry; systematic review | Virtual chemical laboratories | Cognitive outcomes are often comparable or better, while skill-based outcomes and explicit learning theory are less studied. |
| Corter et al. (2011) | Undergraduate engineering | Hands-on, remote, simulated labs | Learning depended on both laboratory format and the coordination of individual/group activity; real and simulated data created different process demands. |
| Li & Liang (2024) | Engineering; meta-analysis | Virtual laboratories | Overall Hedges' g = 0.686 across included engineering studies; authors conclude virtual labs should complement, not fully replace, hands-on labs. |
| Hamed & Aljanazrah (2020) | University general physics | Virtual experiments + conventional lab | Virtual experiments supported achievement and practical learning in a blended physics-laboratory context, while implementation and learner support remained important. |

| Source | Context | Modality / design | Main findings or condition |
|---|---|---|---|
| Fadda et al. (2022) | Secondary STEM; second-order review | Virtual/remote laboratories | Online laboratories were broadly comparable to real labs and more effective when integrated with traditional teaching and adequate teacher feedback. |

## Conceptual understanding and achievement

Evidence for conceptual learning is generally favorable but heterogeneous. In undergraduate physics, Zacharia and Olympiou (2011) found virtual and physical manipulation similarly effective for conceptual understanding under controlled instructional conditions, while Darrah et al. (2014) reported comparable measured learning between virtual and hands-on introductory physics labs. In electrochemistry, Hawkins and Phelps (2013) found no overall significant difference between virtual and traditional groups on pre/post and hands-on setup measures, although some item-level differences appeared. In secondary chemistry, Zendler and Greiner (2020) similarly found computer simulation and experimental instruction to perform comparably for key learning outcomes.

Recent meta-analytic evidence is encouraging but should be interpreted within discipline and design. Li and Liang (2024) synthesized engineering studies and reported an overall Hedges' g of 0.686 (95% CI 0.414-0.959) in favor of virtual-laboratory-supported outcomes, while also concluding that virtual laboratories cannot completely replace hands-on engineering laboratories. This meta-analytic finding provides evidence of a positive effect within the engineering education studies reviewed, while reinforcing the importance of interpreting outcomes in relation to disciplinary context, instructional design, and the complementary role of hands-on laboratory experiences.

## Practical and inquiry skills: where blending matters

Practical learning is multidimensional. Virtual environments can strengthen procedural sequencing, planning, interpretation, and confidence before students encounter scarce or hazardous equipment. Bortnik et al. (2017) found value in a virtual pre-laboratory component for analytical chemistry research practices, and Kolil et al. (2020) reported improvements in experimental self-efficacy in chemistry. Paxinou et al. (2020) provides evidence that virtual preparation in microscopy can support transfer to real equipment-related performance.

However, physical laboratories expose learners to friction, noise, calibration, breakage risk, material variation, unanticipated observations, and the embodied coordination of tools. Those experiences matter where the learning objective is competence with real apparatus. The strongest design response is therefore often blended or sequential. Olympiou and Zacharia (2012) and Kapici et al. (2019) both show benefits from combining modalities based on complementary affordances, a pattern also identified in the second-order review by Fadda et al. (2022). This supports a 'virtual for preparation, visualization, repetition and conceptual inquiry; physical for embodied practice, real measurement and troubleshooting' logic, while recognizing that the precise balance will vary by discipline.

## Engagement, self-efficacy, and the immersion paradox

Many virtual-laboratory studies report positive engagement or learner acceptance. Gamified biotechnology simulation can motivate participation (Bonde et al., 2014); chemistry platforms have been associated with improved self-efficacy or favorable user experience (Agbonifo et al., 2020; Kolil et al., 2020; Peechapol, 2021). Dyrberg et al. (2017) likewise found that tertiary biology students felt more confident and comfortable with laboratory equipment

after virtual pre-laboratory work, although they did not prefer virtual laboratories to real laboratories. These outcomes are educationally relevant because confidence and willingness to practice affect persistence.

Nevertheless, the Makransky et al. (2019a) experiment cautions against assuming that a more immersive interface produces better learning. In that study, immersive VR substantially increased presence but reduced learning and increased cognitive load compared with desktop presentation. The finding directly supports the cognitive-load component of the analytical framework: technological richness can either focus attention or compete with the cognitive processes needed to organize and integrate new knowledge. For resource-constrained settings, it also challenges the idea that high-cost immersive hardware is a prerequisite for an effective virtual laboratory.

### Equity: access is necessary but not sufficient

Virtual laboratories can expand the number of learners who encounter a practical task when physical space, consumables, or equipment are limited. They also enable repetition without consuming materials and can support learners who cannot be present in a laboratory at a fixed time. These characteristics are valuable for equity, but they describe potential access, not guaranteed educational equity.

Four interrelated conditions emerge as particularly relevant to understanding whether expanded technological access can translate into meaningful and potentially equitable learning opportunities. First, the platform must be technically reachable through available devices, electricity, connectivity, and accessibility features. Second, teachers must be able to orchestrate the activity and connect it to disciplinary concepts and assessment. Third, learners need guidance that supports inquiry without turning the activity into passive clicking. Fourth, the curriculum must provide a route from simulated practice to authentic practical competence where physical skill is required. If any of these conditions are absent, virtual laboratories may reproduce a digital divide inside the practical curriculum. Equity should therefore be evaluated through participation, quality of experience, learning, and opportunity for progression, not by software availability alone.

### Differences by discipline and context

Disciplinary context shapes what can be virtualized well. Chemistry and biology often benefit from visualizing molecular or microscopic processes, rehearsing hazardous procedures, and repeating workflows without reagent cost. Physics simulations can allow rapid manipulation of parameters that are difficult to vary in a physical setup. Engineering virtual laboratories can support system behavior, instrumentation logic, and pre-laboratory preparation, but competence in assembly, wiring, calibration, tolerances, maintenance, and fault diagnosis often requires real equipment. This explains why engineering evidence increasingly favors an auxiliary or blended role rather than full substitution (Li & Liang, 2024).

Educational level also matters. Younger learners may need stronger scaffolding and teacher orchestration; university learners may be better able to interpret abstract models but still require authentic equipment exposure for professional competence. Learners with low prior digital familiarity may spend cognitive resources on interface navigation rather than the target concept. Consequently, implementation should begin from learner and curriculum requirements, not with the novelty of technology.

### Implementation principles for resource-constrained environments

The synthesis yields six practical principles. First, define the learning outcome before selecting the technology: conceptual visualization, procedural rehearsal, equipment competence, inquiry, or assessment may require different designs. Second, prefer low-friction access - offline capability, local coaching, modest hardware demands, and shared-device compatibility - where connectivity is uncertain. Third, position the virtual laboratory

within a teaching sequence, with preparation, prompts, prediction, feedback, reflection, and post-lab discussion. Fourth, train teachers in both technical operation and pedagogical orchestration. Fifth, retain physical or remote access for outcomes requiring real equipment interaction, and use virtual practice to make scarce physical time more productive. Sixth, evaluate equity using disaggregated participation and learning data rather than assuming universal benefit from digital availability.

These principles also offer a globally transferable contribution. Resource constraints vary in form: a rural school may lack equipment and broadband; a large university may face overcrowding; a distance learner may lack campus access; a specialist engineering laboratory may have expensive equipment available only for limited hours. An affordance-and-conditions framework can guide decisions across all of these contexts.

The international scholarly contribution of this review lies in reframing virtual-laboratory effectiveness as a relationship between technological affordances, learning mechanisms, and contextual conditions rather than as an inherent property of the technology itself. This perspective provides a common analytical basis for comparing STEM learning opportunities across educational systems with different infrastructure, resources, and pedagogical capacities. It also positions educational equity as an outcome requiring evidence of meaningful participation and learning, rather than merely expanded technological access. The proposed framework therefore offers transferable principles for international STEM education research while recognizing that their effectiveness requires contextual validation.

## Integrated interpretation through the theoretical framework

The reviewed evidence is broadly consistent with the three theoretical perspectives integrated in Figure 1, although the proposed relationships among technological affordances, learning mechanisms, implementation conditions, and outcomes have not been tested as a unified explanatory model. Constructivist benefits appear when students actively manipulate variables, test predictions, and use feedback to revise explanations. Experiential-learning benefits become stronger when simulation is part of a cycle that includes reflection and transfer to authentic practice. Cognitive-load benefits occur when the virtual environment simplifies irrelevant complexity, sequences tasks, or makes invisible processes visible; they weaken when interface demands or immersive detail compete with the learning objective.

This integrated interpretation helps explain apparently contradictory findings. A virtual laboratory can be effective in one study and less effective in another without either result being anomalous because the interventions may differ in guidance, learner experience, visual complexity, assessment target, and relationship to hands-on work. Importantly, the available evidence is uneven across outcome domains. Conceptual understanding is more extensively investigated than authentic practical competence, while equity-related outcomes are frequently inferred from access conditions rather than measured through disaggregated learner performance. This imbalance limits the strength of conclusions regarding equitable learning gains and highlights the need to distinguish demonstrated educational effects from theoretically plausible implementation benefits.

Table 3. Quality and risk-of-bias considerations used in the synthesis.

| Appraisal domain | Stronger evidence pattern | Recurring limitation / interpretation |
|---|---|---|
| Design and comparison | Controlled comparisons or clearly described pre/post designs aligned with the research question. | Convenience allocation and short interventions limit causal and long-term inference. |
| Outcome measurement | Conceptual tests, authentic task measures, or triangulation across quantitative and qualitative evidence. | Self-report and satisfaction are often overused; practical skills are less frequently assessed. |

| Appraisal domain | Stronger evidence pattern | Recurring limitation / interpretation |
|---|---|---|
| Intervention description | Clear distinction among virtual, remote, immersive-VR and hands-on formats, plus instructional supports. | Terminology is inconsistent and sometimes obscures what learners actually do. |
| Transfer and authenticity | Assessment includes performance on real equipment or later hands-on work. | Many studies stop at knowledge tests and do not measure transfer to physical practice. |
| Context and equity | Reports device/infrastructure conditions and learner/teacher characteristics. | Low-resource settings are underrepresented, limiting direct transfer of conclusions. |

## CONCLUSIONS

Virtual laboratories are credible components of STEM practical education, but the evidence does not support treating them as universal substitutes for physical laboratories. Across the reviewed literature, virtual environments commonly support conceptual understanding, visualization, repeated practice, engagement, and preparation. The most persuasive evidence favors deliberate complementarity: virtual laboratories can make scarce physical laboratory time more productive, while physical experiences remain important for tactile, procedural, measurement, and troubleshooting competencies.

The review also sharpens the equity claim. Digital access can reduce one barrier while introducing others. Devices, connectivity, electricity, accessibility, teacher capability, curriculum alignment, and instructional guidance mediate whether nominal access becomes meaningful participation and learning. For resource-constrained education, the most equitable virtual laboratory may therefore be a robust, offline-capable, pedagogically guided platform rather than the most immersive or technically elaborate system.

Future implementation should be evaluated against specific learning outcomes and equity indicators, with comparative designs that measure not only test scores but also inquiry skill, real-equipment transfer, procedural competence, learner participation, teacher workload, infrastructure burden, and total cost. A blended, affordance-based approach provides the strongest basis for resilient and scalable practical STEM learning.

For the international STEM education community, the review provides a conceptual basis for evaluating virtual laboratories according to both learning effectiveness and equity-related implementation conditions. The principal conceptual contribution is an affordance–mechanism–condition framework that distinguishes technological availability from meaningful learning opportunities and educational equity. By linking laboratory modalities with pedagogical processes and contextual constraints, the framework provides testable propositions for comparative STEM education research, although its explanatory relationships require further empirical validation.

## LIMITATIONS AND FURTHER RESEARCH

This review has several limitations. First, it synthesizes heterogeneous modalities, disciplines, age groups, and outcome measures; a single pooled effect estimate would therefore be misleading. Second, the original screening record preserved aggregate PRISMA counts but not database-specific yields or itemized full-text exclusion reasons, limiting complete retrospective reproducibility. Third, English-language publication and the 2010-2024 core window may omit relevant studies. Fourth, much of the evidence originates from institutions with relatively reliable digital infrastructure, so transfer to severely resource-constrained settings should be tested rather than assumed.

Further research should prioritize pragmatic studies in low-resource and rural settings, including offline-first deployments and shared-device models. Studies should compare virtual-only, physical-only, and deliberately

blended sequences; report learner and teacher characteristics; measure practical transfer to real equipment; examine accessibility for learners with disabilities; and include longitudinal outcomes. Cost analyses should include licensing, hardware replacement, electricity, connectivity, teacher preparation, technical support, and the opportunity cost of physical laboratory time. These directions would move the field from broad claims about digital access to evidence about sustainable and equitable practical STEM learning.

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