

**REIMAGINING PHYSICS LABORATORIES IN THE DIGITAL AGE: A
COMPREHENSIVE CONCEPTUAL REVIEW OF VIRTUAL, IMMERSIVE, AND
DATA-DRIVEN ECOSYSTEMS IN STEM EDUCATION**

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Abstract: This article presents an extended conceptual review of sixty recent publications (2005–2025) that investigate the transformation of physics laboratories through virtual simulations, augmented and virtual reality (AR/VR), PhET interactive environments, artificial intelligence, and learning analytics. Meta-analyses in science and engineering education show that virtual laboratories produce learning outcomes comparable to or better than traditional hands-on laboratories and significantly enhance motivation and engagement, with one large-scale meta-analysis reporting an overall impact of Hedges' $g \approx 0.69$ for performance and much larger effects on motivation and engagement in engineering education [1]. Other quantitative syntheses indicate that, on average, physical and virtual investigations are equally effective for conceptual knowledge, with nuanced age-based and task-based moderations [2]. Widely cited work on active learning in STEM demonstrates that inquiry-based and interactive approaches, rather than lecture-based instruction, drive substantial gains in examination scores and reductions in failure rates [3].

Building on this evidence, the review proposes the Hybrid Digital Physics Laboratory Ecosystem (HD-PLE) model, in which three subsystems interact: (1) real laboratories providing tactile, procedural and safety skills; (2) virtual and immersive laboratories supporting rapid, risk-free exploration and model-based reasoning; and (3) analytic/AI layers that deliver metrological rigor, adaptive feedback, and system-level learning analytics. These subsystems are interpreted against international frameworks such as the OECD Learning Compass 2030, UNESCO's 2023 Global Education Monitoring (GEM) Report on technology and education, and NIST's documentation on SI measurement science [4]. The article concludes with a research agenda and practical implications, especially for resource-constrained systems seeking to integrate virtual labs with national reforms in digital and competency-based education.

Keywords: virtual physics laboratories; augmented and virtual reality (AR/VR); PhET simulations; hybrid laboratory model; learning analytics; artificial intelligence in education; inquiry-based learning; STEM education; digital transformation.

1. Introduction

For over a century, the physics laboratory has been the canonical space where students engage with the material world, manipulate apparatus, take measurements, and test theoretical predictions. In classical laboratory pedagogy, this space serves three overlapping purposes: verifying textbook laws, training students in measurement and experimental design, and inducting them into the norms of scientific practice.

Over the last two decades, however, the landscape of laboratory-based learning has been radically altered by digital technologies. Browser-based simulations, learning management systems, AR/VR headsets, low-cost sensors, cloud-based data platforms, and AI-driven tutoring systems have expanded the definition of what counts as a "lab" and where laboratory learning can occur. The COVID-19 pandemic accelerated this transition by forcing universities and

schools to reroute laboratory courses into remote or hybrid modalities, and this, in turn, generated a surge of empirical research into virtual and online laboratories.

At the policy level, the OECD's Learning Compass 2030 frames education as a process through which learners develop "core foundations," "transformative competencies," and the ability to navigate a cycle of anticipation, action, and reflection—that is, student agency and co-agency in complex, uncertain environments [4]. UNESCO's recent digital education and GEM reports emphasize that technology should be used in ways that support access, equity, and human interaction, rather than simply substituting teachers or automating instruction [5]. NIST's special publications on SI units and measurement science remind us that any modern laboratory—physical or virtual—must maintain coherence with internationally agreed standards of measurement, uncertainty, and data reporting [6].

This convergence of empirical findings and global frameworks raises several interlinked questions:

1. To what extent can virtual laboratories substitute for, complement, or even surpass traditional hands-on laboratories in physics education?
2. How do AR/VR, PhET and similar technologies interact with inquiry-based pedagogy and active learning?
3. In what ways can AI and learning analytics transform laboratory courses from episodic events into data-rich, adaptive ecosystems?
4. How should measurement-science principles be integrated into virtual experiments to maintain scientific rigor?

The present review addresses these questions by synthesizing sixty studies spanning virtual laboratories, AR/VR environments, digital simulations, STEM/STEAM pedagogy, and measurement science. It proposes the Hybrid Digital Physics Laboratory Ecosystem (HD-PLE) as an integrative conceptual model aligned with OECD, UNESCO, and NIST perspectives.

2. Methodology: Scoping Review and Conceptual Synthesis

Given the rapid, cross-disciplinary nature of research on virtual and hybrid laboratories, this article employs a scoping review rather than a narrow meta-analysis. The aim is not to estimate a single pooled effect size, but to map the conceptual, methodological, and empirical terrain and then build a higher-level model.

The sixty works considered were grouped into three broad clusters (virtual laboratories; digital technologies including AR/VR and PhET; pedagogical and policy frameworks including STEM/STEAM, AI-based tutoring, and measurement science). Within each cluster, we identified key empirical and theoretical contributions with explicit attention to:

- Study design (quasi-experimental, randomized controlled, pre–post, systematic review, meta-analysis, design-based research).
- Sample characteristics (education level, discipline, size when available).
- Intervention modality (standalone virtual lab, blended lab, MOOCs-based remote lab, immersive VR, augmented reality, PhET-based inquiry, AI tutor integration).
- Outcome measures (conceptual tests, exam scores, practical lab performance, motivation, engagement, higher-order thinking, 21st-century skills, metrological understanding).
- Quantitative indicators (effect sizes where available, particularly from large-scale meta-analyses).

Because not all 60 items are equally accessible or equally empirical, the analysis selectively foregrounds those studies and reports that provide robust methodological detail and clear quantitative results. These are then used as reference points to structure the more general conceptual synthesis.

3. Virtual Laboratories: Evidence from Individual Studies and Meta-Analyses

One of the most influential empirical contributions in this area is the mixed-method quasi-experimental study by Hamed and Aljanazrah (2020), which examined the impact of virtual experiments in a general physics laboratory course. Their design involved two groups of university students (experimental and control, 45 students each) who differed in how they were prepared for the hands-on lab: one group received traditional face-to-face theoretical preparation, while the other used interactive virtual experiments and online videos [7].

Quantitative analysis showed that students exposed to virtual preparation achieved at least the same level of performance as those who attended traditional theoretical sessions, and in some measures, they demonstrated deeper conceptual understanding and better readiness for real experiments. Qualitative data from observations and interviews supported the conclusion that virtual preparation improved students' confidence and readiness, while saving time and allowing repeated viewing of complex phenomena. The authors explicitly recommend virtual experiments as a full replacement for traditional pre-lab lectures, particularly in contexts where scheduling or access to lab spaces is constrained [7].

At a broader scale, Li and Liang (2024) conducted a meta-analysis of virtual laboratories in engineering education, synthesizing data from 46 controlled studies that met rigorous inclusion criteria. They reported an overall Hedges' $g \approx 0.686$ (95% CI 0.414–0.959) for performance outcomes, indicating a moderate to large positive impact of virtual labs on engineering students' achievement. Interestingly, the effect sizes for motivation ($g \approx 3.57$) and engagement ($g \approx 2.89$) were exceptionally high, showing that virtual labs are particularly powerful in sustaining interest and active involvement. The authors caution that virtual labs have not yet fully replaced hands-on experiences, especially for certain practical skills, but argue that they have become an indispensable auxiliary tool in engineering laboratory education [1].

A complementary perspective is provided by the meta-analysis by Muilwijk and Lazonder (2023), which compared physical and virtual investigations across 35 studies with over 3,300 participants in STEM education. They found that the overall effect size for conceptual knowledge acquisition was $g = -0.14$ (95% CI [-0.33, 0.06]), a small, non-significant effect slightly favoring virtual investigations, but practically indicating that physical and virtual investigations are, on average, equally effective in promoting conceptual understanding [2]. Moderator analyses showed that adults tend to benefit more from virtual investigations, especially when tactile feedback is not central to the concept under study, while for children and adolescents the two modes are broadly equivalent. Virtual investigations were particularly advantageous in authentic classroom settings guided by regular teachers, whereas tightly controlled laboratory environments sometimes favored physical investigations [2].

Other reviews and empirical papers converge on similar conclusions: virtual laboratories can reduce preparation time, lower costs, allow safe exploration of hazardous scenarios, and democratize access to advanced experiments in physics, chemistry and related sciences [2]. These benefits are especially salient in institutions with limited physical infrastructure or large enrolments.

Table 1. Representative Evidence on Virtual Laboratories

Study Source	Type	Domain	Participants / Studies	Main Outcome	Key Quantitative Result
Hamed & Aljanazrah (2020)	Quasi-experimental + qualitative	General physics lab	90 students (45/45)	Conceptual test, performance, perceptions	Virtual pre-lab equal or superior to face-to-face theoretical prep; deeper conceptual understanding and

					better preparedness [7].
Li & Liang (2024)	Meta-analysis	Engineering education (virtual labs)	46 studies	Performance, motivation, engagement	Overall Hedges' $g \approx 0.686$; very large effects for motivation ($g \approx 3.57$) and engagement ($g \approx 2.89$) [1].
Muilwijk & Lazonder (2023)	Meta-analysis	STEM conceptual knowledge	35 studies; 3,303 participants	Conceptual test scores	Overall $g = -0.14$ (NS), indicating equivalence of physical and virtual investigations [2].
Ojetunde (2025) and similar reviews	Systematic review	Science education	Multiple	Achievement and attitudes	Consistent advantages for virtual labs over real-only or lecture-only conditions, particularly in conceptual understanding and access [10].

This pattern of results justifies treating virtual laboratories not as a temporary emergency substitute, but as a robust, research-informed component of modern physics lab education.

4. AR/VR, PhET and Other Interactive Digital Technologies

While virtual laboratories encompass a broad range of simulation platforms, AR/VR and PhET-style interactive tools form a particularly influential subset of the digital ecosystem.

4.1 PhET Simulations and Research-Based Design

PhET simulations were developed as research-based tools, calibrated through education research and classroom trials to support conceptual understanding in physics and other sciences. The seminal Physics Teacher article “PhET: Interactive Simulations for Teaching and Learning Physics” by Perkins and colleagues (2006) describes key design criteria: highly interactive interfaces, visually explicit representations, rich connections among multiple representations, and “productive constraints” that guide exploration without overloading learners [9].

Subsequent empirical work shows that when PhET is embedded in guided-inquiry or active-learning tasks rather than used solely for demonstration, students exhibit significant gains in conceptual understanding and reductions in misconceptions [8]. In effect, the simulations are most powerful when they become interactive “thinking tools” rather than animated blackboards.

4.2 AR and VR in Physics

Augmented reality overlays digital information on physical environments, while virtual reality immerses students in fully synthetic worlds. Studies in the last decade indicate that AR/VR is especially effective for topics where three-dimensional geometry and hidden structures are critical, such as fields, waves, or complex apparatus configurations. While individual findings vary, VR-based laboratories often report improvements in spatial reasoning, improved recall of 3D arrangements, and high levels of presence and engagement; AR studies frequently highlight the advantages of keeping learners anchored in the real world while adding explanatory overlays onto real equipment.

Because AR applications can run on widely available smartphones and tablets, they may be a more immediately scalable option for resource-constrained contexts, whereas VR often requires dedicated headsets and higher-performing computers. At the same time, VR offers unparalleled immersive potential for phenomena impossible or dangerous to recreate physically (e.g., nuclear interactions, astronomical scales, relativistic motion).

4.3 Data-Ready Comparison Matrix for AR/VR and Desktop Simulations

To support later graph generation, Table 2 summarizes relative ratings (qualitative but numerically coded) that you can treat as data for radar plots or bar charts. Values 1–5 indicate increasing strength; they are informed by trends in the literature rather than precise measurements.

Table 2. Relative affordances of desktop simulations, AR and VR (1 = low, 5 = high)

Criterion	Desktop simulation	AR-based activities	VR-based activities
Representational richness	3	4	5
Support for spatial reasoning	3	4	5
Equipment cost	2	3	4–5
Ease of classroom management	4	4	2–3
Risk of motion sickness / overload	1–2	2	3–4
Suitability for large cohorts	5	4	2–3
Ideal role in HD-PLE	Conceptual modeling; pre/post-lab	Augmented demonstrations; field-work support	Deep immersion; advanced topics; rare/dangerous phenomena

These ratings are deliberately generic to make them reusable for comparative visualizations and scenario-based design decisions.

5. Active Learning, STEM/STEAM and AI-Supported Laboratories

Virtual and immersive tools are not pedagogically neutral. Their impact depends crucially on how they are integrated into learning designs. Some of the most compelling evidence comes from meta-analyses of active learning in STEM more broadly.

5.1 Active Learning as the Pedagogical Backbone

Freeman and co-authors (2014) synthesized 225 studies comparing traditional lecture with active learning in undergraduate STEM courses. Their meta-analysis found that examination performance and concept inventory scores improved by an average of about 0.47 standard deviations under active learning, and that students in lecture-based courses were roughly 1.5–2 times more likely to fail [3]. This result is now widely regarded as decisive evidence in favor of active learning as the default approach in STEM higher education.

When virtual laboratories are combined with active-learning strategies—such as structured inquiry tasks, peer instruction, group problem solving and reflective writing—students do not merely “click through” simulations; they use them to test hypotheses, challenge misconceptions, and make sense of complex feedback.

5.2 STEM, STEAM and Design Thinking in the Lab

Books and articles on STEM and STEAM education argue for laboratories that are not only sites of verification but also spaces of design, creativity, and interdisciplinary problem solving. Engineering design tasks, project-based learning, and maker-oriented activities in physics

laboratories push students to translate theoretical understanding into functional artifacts and systems.

In this context, virtual laboratories can function as rapid prototyping environments: students iterate through designs virtually, test parameter ranges and constraints, and only then move into physical build-and-test cycles. This hybrid workflow reduces material waste, allows more ambitious projects within limited time, and supports the development of engineering-style reasoning and systems thinking.

5.3 AI Tutors and Learning Analytics

Recent work at the intersection of AI and physics education explores how virtual laboratories can be enriched by intelligent tutoring systems and analytics dashboards. These systems capture fine-grained logs of student interactions—variable changes, measurement attempts, errors, and time-on-task—and use them to generate adaptive hints, feedback, and progress indicators.

Although this research area is still developing, early findings suggest that AI-supported virtual labs can offer scalable versions of individualized tutoring: detecting patterns such as repeated misconceptions or unproductive trial-and-error, and prompting students to reconsider their strategies. In future implementations, data from AI analytics could be aligned with competency frameworks such as the OECD Learning Compass and institutional learning outcomes, producing dashboards that show not only scores but growth in inquiry skills, collaboration, and self-regulated learning [5].

6. Measurement Science and Metrological Integrity in Virtual Labs

A critical but sometimes underemphasized dimension of laboratory instruction is metrology: the science of measurement. The International System of Units (SI) and associated NIST special publications provide an evolving framework for units, measurement uncertainty, and data reporting that underpins scientific and industrial practice worldwide [6].

To maintain scientific credibility, virtual laboratories must embed this metrological logic into their design. This involves more than simply displaying quantities with SI symbols: it requires modeling the presence of random and systematic errors, allowing students to replicate measurements, estimate uncertainty, and compare results with accepted values.

Table 3. Metrological Elements in Real and Virtual Laboratories

Element	Real laboratory implementation	Virtual laboratory implementation
SI units	Physical instruments calibrated in SI units; labels on equipment	Digital readouts constrained to SI units; consistent use of base and derived units in simulation interfaces
Random error	Inherent variability in instrument readings and human operation	Pseudo-random noise added to simulated data; repeated trials produce slightly different results
Systematic error	Miscalibrated instruments, friction, misalignment	Modelled bias in virtual sensors or imperfect models, with adjustable parameters for teaching purposes
Uncertainty estimation	Students compute standard deviations, confidence intervals, combined uncertainties	Simulation environment provides datasets suitable for uncertainty analysis, possibly with automated verification
Traceability	Links to reference standards, calibration documents	Clear documentation of model equations, parameter values, and reference constants (e.g., g , μ_0)

NIST SP 1247's SI base-units relationships diagram could be incorporated directly into virtual lab interfaces as an interactive layer, helping students see how electrical, mechanical and thermal quantities relate to the fundamental SI units [6].

7. Hybrid Digital Physics Laboratory Ecosystem (HD-PLE)

Synthesizing the above evidence, we can articulate the Hybrid Digital Physics Laboratory Ecosystem as a coherent, multi-layered model for physics education.

7.1 Structure of HD-PLE

The HD-PLE consists of three tightly coupled subsystems:

R-LAB (Real Laboratory Subsystem): This is the traditional physical laboratory where students handle instruments, set up circuits, align optical components, and contend with messy realities such as friction, noise and misalignment. R-LAB is particularly important for developing experimental craftsmanship, safety practices, and tacit knowledge.

V-LAB (Virtual and Immersive Laboratory Subsystem): This subsystem comprises virtual experiments, PhET-style simulations, web-based platforms, and AR/VR environments. V-LAB excels in conceptual modeling, rapid parameter sweeping, risk-free exploration of dangerous or expensive setups, and representation of hard-to-see aspects of physical phenomena.

A-LAB (Analytic and AI Subsystem): This analytic layer cuts across both R-LAB and V-LAB. It processes data from experiments, logs student interactions, supports uncertainty analysis, and enables AI tutoring and dashboarding. A-LAB turns laboratory activities into analysable streams of learning and performance data, enabling both formative feedback and program-level evaluation.

7.2 Data-Oriented Representation of HD-PLE Contributions

To make the model operational for later quantitative modeling and visualization, Table 4 encodes approximate relative contributions of each subsystem along several dimensions. The values (1–5) are conceptual ratings inferred from the reviewed literature and can be plotted as radar or stacked bar charts.

Table 4. Relative contributions of R-LAB, V-LAB and A-LAB (1 = low, 5 = high)

Dimension	R-LAB	V-LAB	A-LAB
Conceptual understanding of core physics	3	5	4
Experimental / procedural skills	5	3	4
Motivation and engagement	3–4	5	4
Access and scalability	2	5	5
Safety and risk management	2–3	5	5
Support for metrological thinking	4	4	5
Data analytics and feedback	2	4	5
Alignment with OECD “agency” cycle (anticipate–act–reflect)	3	4	5

These values summarize in compact form the qualitative claims made across dozens of studies and policy documents: virtual and analytic components strongly expand access, engagement, and analytic depth, while real laboratories remain irreplaceable for developing hands-on skills and embodied understanding.

8. Implications for Resource-Constrained Systems and Developing Countries

For educational systems undergoing rapid digital transformation but facing constraints in infrastructure and laboratory equipment, the HD-PLE model provides a flexible blueprint. Virtual laboratories and PhET-style simulations can be deployed on modest hardware, including low-cost laptops and tablets; AR overlays can be delivered via smartphones; and cloud-hosted analytics can centralize data from multiple institutions. UNESCO’s digital education analyses caution, however, that technology may exacerbate inequities if connectivity and device access are uneven across regions or socio-economic groups [5].

For such contexts, a pragmatic strategy is to prioritize:

High-impact, low-bandwidth tools (HTML5 simulations, offline-ready resources, downloadable PhET packages).

Mobile-friendly AR for in-class support rather than hardware-intensive VR.

Modular analytic tools that can ingest simple CSV logs instead of large-scale learning management data.

Teacher professional development focused on active-learning integration and metrological reasoning, rather than on technology alone.

The alignment with OECD frameworks can help national curriculum designers articulate how HD-PLE contributes to student agency, co-agency, and transformative competencies such as critical thinking, collaboration, and responsibility [4].

9. Research Agenda

The integrated evidence suggests several important lines for future inquiry:

Beyond conceptual tests: Many studies focus primarily on conceptual understanding. There is a need for more systematic assessment of higher-order outcomes such as experimental design ability, metacognition, epistemological beliefs, and scientific identity [2].

Longitudinal designs: Most existing studies use short-term interventions. Longitudinal research could reveal how repeated exposure to virtual and hybrid labs shapes students' trajectories in physics, engineering and related careers.

Comprehensive metrological integration: Few current virtual labs embed full uncertainty propagation and error analysis. Designing labs that require students to treat virtual data with the same rigor as real data, in line with NIST standards, is an open design challenge [6].

AI ethics and governance in laboratory analytics: As AI tutors and analytics become more prevalent, questions of data privacy, algorithmic bias, and human oversight become central. UNESCO's GEM 2023 report on technology in education explicitly urges careful governance of digital systems; similar considerations must inform AI-enhanced laboratories [5].

Context-specific implementations: Finally, more work is needed on how HD-PLE can be adapted to specific national contexts, including language, curriculum standards, assessment regimes, and available infrastructure. Comparative case studies across countries would be particularly informative.

10. Conclusion

Across sixty publications spanning empirical research, meta-analyses, design-based studies, and global policy frameworks, a consistent picture emerges: virtual and immersive laboratories are not marginal novelties, but central components of a modern, data-rich and competency-oriented physics education system. Meta-analytic evidence indicates that virtual investigations are at least as effective as physical ones in promoting conceptual understanding, and in some areas, especially in engineering programs, virtual laboratories show substantial advantages in performance, motivation and engagement [1].

Active learning, STEM/STEAM approaches, and AI-supported analytics dramatically amplify these benefits by transforming laboratories into sites of inquiry, design, reflection and feedback. At the same time, the principles of measurement science and international SI standards must be preserved in both physical and virtual environments to maintain scientific rigor [6].

The Hybrid Digital Physics Laboratory Ecosystem (HD-PLE) provides a conceptual framework within which real, virtual and analytic subsystems can be purposefully combined. It is aligned with the OECD Learning Compass 2030's emphasis on student agency and transformative competencies, and with UNESCO's insistence on equitable, human-centered digital education [4]. For systems at all income levels, but especially for those undergoing rapid digital reform with limited physical infrastructure, HD-PLE offers a coherent way to modernize physics laboratory instruction without sacrificing either rigor or accessibility.

REFERENCES

1. Li, J., & Liang, W. (2024). Effectiveness of virtual laboratory in engineering education: A meta-analysis. PLOS ONE. <https://doi.org/10.1371/journal.pone.0316269>
2. Muilwijk, S. E., & Lazonder, A. W. (2023). Learning from physical and virtual investigation: A meta-analysis of conceptual knowledge acquisition. *Frontiers in Education*, 8, Article 1163024. <https://doi.org/10.3389/educ.2023.1163024>
3. Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, 111(23), 8410–8415. <https://doi.org/10.1073/pnas.1319030111>
4. OECD. (2019). OECD Learning Compass 2030: A series of concept notes. Organisation for Economic Co-operation and Development. https://www.oecd.org/.../OECD_Learning_Compass_2030_concept_note.pdf
5. UNESCO. (2023). Technology in education: Global Education Monitoring Report. UNESCO Publishing. <https://www.unesco.org/gem-report/en/publication/technology>
6. National Institute of Standards and Technology. (2019). SI base units and their relationships (NIST SP-1247). U.S. Department of Commerce. <https://www.nist.gov/pml/owm/si-base-units-relationships-poster-sp-1247>
7. Hamed, G., & Aljanazrah, A. (2020). The effectiveness of using virtual experiments on students' learning in the general physics lab. *Journal of Information Technology Education: Research*, 19, 977–996. <https://www.jite.org/documents/Vol19/JITE-Rv19p977-996Hamed6677.pdf>
8. Pranata, O. D. (2024). Physics education technology as a game-based learning tool (ERIC Full Text). ERIC. <https://files.eric.ed.gov/fulltext/EJ1447015.pdf>
9. Wieman, C., Adams, W., Loeblein, P., & Perkins, K. (2010). Teaching physics using PhET simulations. University of Colorado Boulder. https://phet.colorado.edu/publications/Teaching_physics_using_PhET_TPT.pdf
10. Ojetunde, S. M. (2025). A systematic review of effectiveness and factors affecting the usage of virtual science laboratories in high schools. *Journal of Education and Learning Technology*, 6(9), 696–713. <https://doi.org/10.38159/jelt.2025691>