American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)

E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Virtual Laboratory Equity in Low-Resource Science Programs

Dr. James Wilson

Associate Professor, University of Cape Town, South Africa

Abstract

Laboratory participation is fundamental to science education because students need opportunities to observe phenomena, manipulate variables, interpret measurements, test hypotheses, evaluate uncertainty, and connect theoretical principles with experimental evidence. Yet access to well-equipped laboratories remains uneven across institutions. Low-resource science programs may face shortages of equipment, consumables, laboratory space, trained technical staff, maintenance capacity, safe experimental facilities, electricity, and reliable internet connectivity. Virtual laboratories provide one mechanism for widening practical-learning opportunities by allowing learners to perform simulated or remotely mediated experiments without continuous access to costly physical infrastructure. India's Virtual Labs initiative, for example, explicitly seeks to provide remote access to simulation-based science and engineering laboratories and identifies inadequate physical laboratory facilities and shortages of trained teachers among the problems it seeks to address.

This paper develops an Equity-Optimized Virtual Laboratory Framework for low-resource science programs. The model argues that virtual-laboratory equity cannot be evaluated merely by counting how many students receive login access. Meaningful equity requires affordability, low-bandwidth functionality, device compatibility, disability accessibility, pedagogical relevance, repeatability, instructor readiness, practical-skill transfer, and continuing access to selected physical experimentation. A 2024 systematic review of 36 virtual-laboratory accessibility studies found substantial potential for inclusion while also identifying continuing barriers related to accessibility, technological resources, and diverse learner needs.

The study employs a conceptual-methodological design with transparent simulation-based analysis. Three science-laboratory delivery models are compared: a resource-constrained physical laboratory, a standard cloud-based virtual laboratory, and an equity-optimized hybrid virtual-laboratory model. The simulated comparison evaluates access coverage, low-bandwidth suitability, accessibility, repeatability, cost efficiency, and practical-skill support. The hybrid model achieves the strongest balanced equity profile because it combines repeatable digital experimentation with selective physical laboratory sessions, downloadable or lightweight simulations, accessibility standards, instructor support, and shared-device strategies. The numerical values are illustrative rather than empirical results.

The paper concludes that virtual laboratories can reduce some forms of science-education inequality but may reproduce or deepen others if platforms assume continuous broadband, powerful personal devices, English-language fluency, unrestricted screen interaction, or high levels of digital literacy. Equitable implementation should therefore follow a virtual-first where appropriate, physical-when-essential, low-bandwidth-by-design model. Virtual laboratories should expand opportunities to experiment, prepare learners for scarce physical laboratory time, and allow repetition, while physical laboratory experiences remain important for instrumentation, material handling, measurement uncertainty, safety practices, troubleshooting, and embodied scientific skills.

Keywords: virtual laboratories, science education equity, low-resource institutions, STEM education, digital divide, practical science education, laboratory accessibility, blended laboratories, low-bandwidth learning, inclusive higher education

1. Introduction

Laboratory education occupies a distinctive place in science because scientific knowledge is not developed solely through reading and explanation; it is also constructed through observation, measurement, manipulation, comparison, error analysis, and experimental judgment. Universities and colleges therefore require laboratory opportunities that allow learners to connect abstract principles with empirical behavior. The difficulty is that meaningful laboratory education can be expensive. Equipment must be purchased and maintained, consumable materials replaced, laboratory space provided, safety procedures enforced, and trained instructors or technicians made available. India's national Virtual Labs platform explicitly identifies the scarcity of good laboratory facilities and trained teachers as barriers that remote simulation-based laboratories are intended to address.

Virtual laboratories can change the economics and availability of practical science learning. They can allow a learner to repeat an experiment without consuming reagents, damaging equipment, creating hazardous conditions, or waiting for limited laboratory space. Reviews of virtual laboratory research have reported benefits including accessibility, flexibility, reduced cost, safe experimentation, and opportunities for repeated practice. In engineering education specifically, a 2024 meta-analysis found that virtual laboratories significantly contributed to educational outcomes but also concluded that they could not yet completely replace hands-on laboratories. This distinction is critical for equity: offering a virtual simulation to students who never obtain experience with real instruments may widen conceptual access while leaving a practical-skills gap intact.

The equity problem is therefore more complex than simple availability. A web-based laboratory may be geographically accessible but unusable for students with unstable connectivity, limited mobile data, shared smartphones, old computers, visual or motor disabilities, or insufficient digital literacy. Deriba, Saqr, and Tukiainen's 2024 systematic review of virtual-laboratory accessibility synthesized 36 studies and found that accessibility must be considered across multiple learner and technology conditions rather than assumed from online availability alone. Broader digital-education evidence similarly shows that unreliable and unaffordable internet connectivity, limited devices, and insufficient digital infrastructure remain significant barriers in some higher-education contexts. An equity-centered design must consequently ask who can actually use the laboratory, under what technological conditions, and with what quality of learning experience.

Existing public initiatives demonstrate both the promise and the design challenge. India's Virtual Labs program provides remote access to science and engineering simulations and is explicitly intended to support institutions with inadequate laboratory facilities. UNESCO's partnership with LabXchange similarly promotes freely available digital science learning resources and virtual laboratory simulations for secondary, postsecondary, and workforce education. At the same time, UNESCO's current higher-education digital-transformation agenda emphasizes that digital learning should be equitable, inclusive, and high quality rather than measured solely by technological adoption. These examples indicate that virtual laboratories can become public educational infrastructure, but only when access, pedagogy, accessibility, and institutional capability are treated together.

The present study develops an equity-oriented model for virtual laboratory adoption in low-resource science programs. Rather than asking whether virtual laboratories are better or worse than physical laboratories in the abstract, the paper examines how combinations of physical, virtual, and low-bandwidth learning resources can reduce unequal access while preserving scientifically important practical competencies. No real institutional experiment or student dataset was supplied; accordingly, the quantitative analysis is explicitly simulated. The contribution is a planning framework through which institutions can evaluate laboratory equity across access coverage, connectivity requirements, accessibility, repeatability, cost efficiency, and physical practical-skill development.

2. Objectives of the Study

2.1 To Define Virtual Laboratory Equity Beyond Digital Access

The first objective is to develop a multidimensional definition of laboratory equity. In this study, equity does not mean that every learner receives identical laboratory resources. It means that students should have a realistic opportunity to achieve the intended scientific learning outcomes despite differences in institutional wealth, connectivity, device ownership, disability status, geography, and prior digital experience.

The framework therefore distinguishes nominal access from effective access. A laboratory is nominally accessible when a link exists. It becomes effectively accessible when students can open it with available devices, understand the interface, use it without excessive connectivity costs, repeat experiments when needed, and obtain instructional support.

2.2 To Identify a Resource-Sensitive Virtual Laboratory Model

The second objective is to determine how low-resource programs can combine virtual and physical laboratory experiences rather than treating them as mutually exclusive alternatives.

Evidence from recent laboratory research supports complementary designs. Studies of hybrid and blended laboratory formats indicate that virtual laboratories can support preparation, repetition, conceptual understanding, and familiarization, while physical activities retain value for actual equipment handling and other embodied skills.

2.3 To Develop an Equity-Oriented Evaluation Framework

The third objective is to identify indicators through which institutions can judge whether virtual-laboratory investments are actually reducing educational inequality.

The proposed assessment examines access coverage, bandwidth requirements, accessibility, device compatibility, learning repeatability, cost efficiency, instructor readiness, practical-skill transfer, and integration with scarce physical laboratory resources.

3. Review of Literature

3.1 Educational Effectiveness and the Limits of Full Substitution

Virtual laboratories have expanded rapidly across engineering, chemistry, physics, health sciences, computing, and related fields. Raman and colleagues' historical and bibliometric review identified cost reduction, accessibility, flexibility, safety, and repeatability among frequently cited advantages of virtual laboratories. Sellberg and colleagues' 2024 scoping review similarly documented the broad use of virtual laboratories across STEM higher education and highlighted their role in supporting different forms of practical and conceptual learning.

Evidence regarding learning outcomes is generally encouraging but does not justify treating virtual laboratories as universal replacements for physical experimentation. Li and colleagues' 2024 meta-analysis of engineering education reported a significant positive effect associated with virtual laboratories while concluding that existing virtual laboratories do not fully substitute for hands-on laboratory experiences. This limitation is pedagogically important because science laboratories develop several kinds of competence simultaneously. Conceptual reasoning can often be simulated effectively, whereas manipulating fragile equipment, connecting real instruments, identifying contamination, reading imperfect measurements, responding to unexpected physical behavior, and following laboratory safety procedures involve additional forms of knowledge.

Recent hybrid-learning studies strengthen the case for complementarity. Zamarreño and colleagues' 2025 work on virtual and remote laboratories in control engineering describes these formats as complementary support for on-site laboratory learning. A 2025 study comparing virtual laboratory simulations with in-person laboratory activities reported comparable performance results and positive student perceptions, with learners showing interest in using virtual simulations as pre-laboratory or supplemental activities. A 2025 undergraduate physics initiative in India likewise reported strong student support for web-based pre-laboratory simulations designed to prepare learners for subsequent physical practicals.

These findings support a preparation–simulation–physical application model. Virtual experimentation can introduce procedures, permit repeated conceptual exploration, and help students understand expected relationships before scarce laboratory time is used. Physical laboratory sessions can then concentrate on skills that cannot be reproduced adequately through simulation.

3.2 Equity, Accessibility, and the Digital Divide

The strongest equity argument for virtual laboratories is that they can extend experimental learning to students who lack local access to sophisticated laboratory infrastructure. India's national Virtual Labs initiative is explicitly organized around this principle and provides remote-access simulation-based laboratories across science and engineering disciplines. In rural or resource-limited education, research has similarly examined virtual laboratories as a means of supplementing conventional practical work where laboratory infrastructure is inadequate.

Yet online access can introduce a second layer of inequality. Deriba, Saqr, and Tukiainen's systematic review found that virtual-laboratory accessibility remains an underdeveloped area and that inclusion depends on more than simply placing laboratories online. Their earlier review of barriers also identified technical and accessibility challenges that can prevent learners from using virtual laboratories effectively. Students with visual, auditory, motor, or cognitive disabilities may face barriers when simulations depend heavily on drag-and-drop interfaces, small visual indicators, color differences, rapid animation, or inaccessible graphical controls.

Connectivity presents another form of exclusion. UNESCO and World Bank evidence on digital higher education continues to identify connectivity, devices, and institutional digital capacity as significant implementation conditions. A simulation requiring persistent high-speed streaming or immersive virtual reality may therefore be pedagogically sophisticated but institutionally inequitable in settings where students depend upon limited mobile data or campus computers shared across large cohorts.

Device assumptions are equally important. A virtual laboratory that operates only on modern laptops or head-mounted virtual-reality hardware can shift the cost of practical education from the institution to the learner. The result may be greater inequality within the same class. Equity-oriented virtual laboratories should consequently support responsive interfaces, modest hardware requirements, asynchronous use, downloadable components where feasible, and institutionally shared access points.

Teacher readiness completes the equity picture. Shambare's research on virtual-laboratory adoption in rural science education emphasizes that teacher acceptance, perceived usefulness, and implementation conditions affect whether virtual laboratories become meaningful teaching resources. Providing software without pedagogical training may therefore increase nominal resources without increasing effective laboratory participation.

3.3 Toward Hybrid and Inclusive Laboratory Ecosystems

An equity-oriented laboratory ecosystem should not begin with the assumption that the most immersive technology is necessarily the most appropriate technology. High-fidelity virtual reality can provide powerful learning experiences, but it can also require expensive devices, substantial computing capability, and greater technical support. Resource-sensitive implementation should instead match technological complexity to learning objectives.

Learning analytics may offer one useful capability. Elmoazen and colleagues' systematic review of learning analytics in virtual laboratories showed that student interaction logs can provide information about laboratory behavior and learning activity. Such evidence could help instructors identify students who repeatedly fail particular procedural steps or never complete assigned activities. In low-resource settings, however, data collection should remain proportionate and should not require expensive analytic infrastructure merely because it is technically possible.

Collaboration is another important design consideration. Kurtz and colleagues' 2025 review found that communication and group-awareness features are increasingly integrated into virtual and remote laboratories and can support collaborative learning. This matters because conventional laboratory education often develops scientific teamwork, communication, division of tasks, and collaborative problem solving. A purely solitary simulation may increase access while losing these social dimensions.

The emerging literature consequently points toward hybrid laboratory ecosystems rather than binary replacement. Physical laboratories, browser-based simulations, remote laboratories, recorded demonstrations, mobile resources, collaborative digital activities, and instructor-facilitated analysis can be combined according to institutional capacity and learning objectives. The research gap lies in designing this combination explicitly around equity, rather than introducing virtual laboratories primarily for modernization or convenience.

4. Research Methodology

4.1 Research Design

The study uses a conceptual-methodological design with simulation-based comparative analysis. No students, instructors, universities, or laboratory facilities were empirically assessed.

The evidence base was constructed from systematic reviews, meta-analyses, higher-education laboratory studies, and institutional or policy sources concerning digital science learning, laboratory accessibility, and resource constraints. Particular emphasis was placed on recent evidence addressing accessibility and hybrid implementation.

The purpose of the simulation is not to estimate actual learning outcomes but to demonstrate how laboratory-delivery strategies can be evaluated simultaneously across multiple equity dimensions.

4.2 Equity-Optimized Virtual Laboratory Framework

Table 1: Equity-Optimized Virtual Laboratory Framework for Low-Resource Science Programs

Equity Domain	Core Institutional Question	Resource-Sensitive Strategy	Intended Educational Benefit
Access Coverage	Can all enrolled students realistically reach laboratory experiences?	Shared campus access, browser delivery, extended access windows	Expands participation beyond limited physical lab capacity
Connectivity	Does learning require continuous high-speed internet?	Low-bandwidth mode, downloadable resources, caching, asynchronous activities	Prevents connectivity from becoming an exclusion mechanism
Device Compatibility	Can the simulation operate on commonly available hardware?	Mobile-responsive and low-specification browser design	Reduces dependence on expensive personal devices
Disability Accessibility	Can students using assistive technologies interact meaningfully?	Keyboard support, text alternatives, captions, scalable interfaces, non-color-dependent cues	Supports inclusive participation
Pedagogical	Does the simulation	Map virtual tasks to course	Prevents technology-

Equity Domain	Core Institutional Question	Resource-Sensitive Strategy	Intended Educational Benefit
Alignment	correspond to actual curriculum outcomes?	experiments and assessment	centered rather than learning-centered adoption
Instructor Capacity	Can teachers integrate and troubleshoot the laboratory effectively?	Orientation, reusable lesson plans, technical support and peer mentoring	Converts access into meaningful use
Practical Skill Transfer	Which outcomes still require real materials and instruments?	Reserve physical sessions for essential hands-on competencies	Prevents conceptual access from replacing embodied laboratory learning
Sustainability	Can the institution maintain the system over several years?	Open/free resources where appropriate, shared procurement, lightweight platforms	Reduces recurring cost and vendor dependence

4.3 Simulation and Equity Metrics

Three laboratory delivery models were constructed for analytical comparison.

- The Resource-Constrained Physical Laboratory Model represents an institution possessing limited but functional physical facilities. It provides strong hands-on experience but has restricted scheduling, equipment availability, and repeatability.
- The Standard Cloud Virtual Laboratory Model represents an internet-dependent digital platform with good access scalability and repeatability but relatively demanding connectivity and limited direct physical skill development.
- The Equity-Optimized Hybrid Virtual Laboratory Model combines low-bandwidth simulations, shared-device access, accessible interfaces, repeated virtual practice, selected physical practicals, and instructor-facilitated integration.

5. Analysis

5.1 Simulated Equity Comparison

Table 2: Simulated Equity Performance of Alternative Science Laboratory Models

Equity Dimension	Resource-Constrained Physical Lab	Standard Cloud Virtual Lab	Equity-Optimized Hybrid Model
Access Coverage	42	82	**91**
Low-Bandwidth	**96**	52	88

Equity Dimension	Resource-Constrained Physical Lab	Standard Cloud Virtual Lab	Equity-Optimized Hybrid Model
Suitability			
Accessibility	58	68	**86**
Repeatability	36	91	**94**
Cost Efficiency	38	78	**89**
Practical Skill Support	**90**	57	84

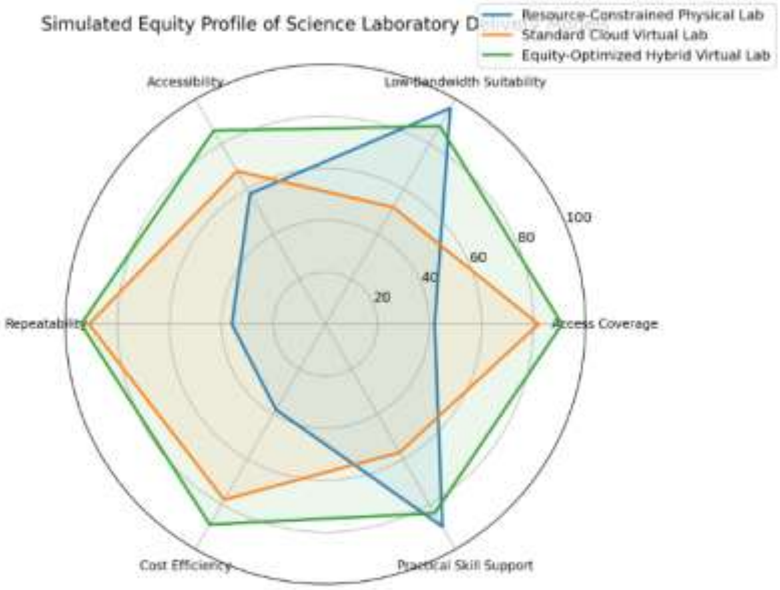
Note: Values are simulated analytical scores from 0–100 and do not represent measurements from actual institutions.

The resource-constrained physical laboratory demonstrates an important strength: students who obtain access interact directly with equipment and therefore receive strong practical-skill opportunities. The problem is distribution. Limited laboratory capacity reduces access coverage and repeated practice.

The standard cloud model reverses several of these weaknesses. More students can access experiments and can repeat them multiple times, but low-bandwidth suitability declines sharply because continuous internet availability becomes part of the educational requirement.

5.2 Radar Analysis of Laboratory Equity

Graph 1: Simulated Equity Profile of Science Laboratory Delivery Models



The radar graph demonstrates that no single delivery mode dominates every dimension. This is academically significant because it prevents virtual-laboratory equity from being reduced to a claim that digital delivery is always superior.

The resource-constrained physical model provides strong low-bandwidth independence and practical-skill development but performs weakly in access coverage, repeatability, and cost efficiency. A standard cloud laboratory provides nearly the opposite profile: strong repeatability and broad reach but greater dependence upon digital infrastructure.

The equity-optimized hybrid model achieves the broadest overall profile because its design objective is not maximum virtualization but balanced access to learning outcomes.

5.3 Proposed Implementation Pathway for Low-Resource Programs

The first implementation stage should identify which laboratory outcomes are conceptual, which are procedural, and which are material or embodied. Conceptual tasks such as exploring variable relationships, predicting trends, comparing models, or repeating experiments under different parameters are particularly well suited to simulation.

The second stage should redesign virtual activities for constrained connectivity. Institutions should favor browser-based or downloadable experiences over unnecessarily bandwidth-intensive immersive environments where the same learning objective can be achieved through lighter technology. UNESCO's wider digital-education agenda emphasizes equitable access rather than technology adoption for its own sake.

The third stage should use virtual laboratories to multiply the educational value of scarce physical laboratory time. Students can complete simulation-based preparation before a physical session, arrive familiar with experimental variables and procedures, and use real laboratory time for equipment operation, measurement, troubleshooting, safety, and interpretation of imperfect real-world results. Evidence from hybrid laboratory studies supports this complementary role.

6. Discussion

6.1 Virtual Access Becomes Equitable Only When Infrastructure Assumptions Are Explicit

The first major implication is that virtual laboratories should not be described automatically as equitable technologies. Their distribution model can remove geographical and physical-infrastructure barriers, but digital participation introduces new requirements. Students require appropriate devices, electricity, sufficient connectivity, digital literacy, and interfaces they can use effectively. The 2024 accessibility review is particularly important because it demonstrates that accessibility in virtual laboratories remains a substantive design problem rather than a property automatically created by online delivery.

Institutions should therefore conduct an access audit before adopting a platform. The relevant question is not how many students own smartphones but whether the complete laboratory activity can be performed on the devices they actually use. Screen size, processing capability, data consumption, browser compatibility, keyboard requirements, and assistive technology compatibility all influence participation.

Low-bandwidth design should be treated as a pedagogical-quality characteristic in resource-constrained environments. A simulation that functions smoothly only on high-speed broadband can unintentionally shift inequality from laboratory equipment to network access. World Bank and UNESCO evidence continues to identify connectivity and infrastructure as significant conditions affecting digital higher-education implementation.

Equity also requires institutional alternatives. Students experiencing connectivity failure should be able to use campus devices, downloadable versions, scheduled access rooms, offline learning packages, or other mechanisms without academic penalty. Equity is strongest when the system anticipates variation rather than treating a technically ideal user as the default learner.

6.2 Hybrid Laboratory Design Protects the Meaning of Practical Science Education

The second implication concerns the risk of confusing access to a simulation with completion of all laboratory-learning objectives. Virtual laboratories can represent scientific systems extremely effectively, but real experimental environments contain uncertainty and complexity that simulations often simplify.

A student working with actual instruments must interpret calibration, noise, imperfect connections, material properties, timing errors, contamination, mechanical resistance, equipment limitations, and unexpected observations. These experiences contribute to scientific judgment.

The 2024 engineering meta-analysis concluded that virtual laboratories provide significant educational benefits while still lacking the ability to replace hands-on laboratories completely. Recent hybrid evidence likewise supports using virtual laboratories before or alongside physical practicals rather than assuming complete substitution.

For low-resource institutions, this finding is encouraging rather than problematic. It means that laboratory equity does not require every learner to receive unlimited physical laboratory time. Virtual laboratories can absorb the parts of practical education that are highly repeatable digitally, allowing scarce physical facilities to be concentrated on the experiences for which real equipment matters most.

A chemistry student, for example, might use a virtual activity repeatedly to understand titration curves before attending a shorter physical practical focused on burette handling, endpoint observation, measurement precision, contamination control, and experimental uncertainty. An engineering student could explore control parameters virtually before operating a real pilot plant. Equity is improved because scarce physical time becomes more educationally productive.

6.3 Equity Requires Institutional Capacity, Not Merely Platform Procurement

The third implication is that institutions should treat virtual laboratories as an educational system rather than software licenses. Teacher preparation, curriculum integration, technical assistance, accessibility testing, assessment design, and maintenance all influence whether students benefit.

Research on virtual laboratories in rural or resource-limited science contexts highlights the importance of teacher perceptions, readiness, and perceived ease of use. A poorly supported instructor may use a sophisticated laboratory as little more than an animation, whereas a well-prepared instructor can use a simple simulation to elicit hypothesis formation, variable manipulation, evidence interpretation, and scientific argument.

Institutional collaboration can reduce implementation cost. India's Virtual Labs project demonstrates the potential of shared national infrastructure rather than requiring every institution to build a separate simulation platform. UNESCO's LabXchange partnership similarly illustrates the role of freely accessible shared science-learning resources. For low-resource programs, collaborative development, open educational resources, national repositories, shared server infrastructure, and consortium procurement may offer greater equity than fragmented institution-by-institution purchasing. The strongest policy objective should therefore be laboratory capability per learner, not the number of virtual platforms adopted. An inexpensive, accessible, curriculum-aligned simulation that functions on ordinary devices and is integrated with targeted physical experimentation may produce greater educational equity than an expensive immersive platform available only to a small proportion of students.

7. Conclusion

Virtual laboratories offer a significant opportunity to expand practical science learning where physical laboratory capacity is insufficient, expensive, geographically inaccessible, or difficult to schedule. They can provide repeated experimentation, safe manipulation of variables, exposure to otherwise unavailable scientific systems, and opportunities for learners to prepare before entering a physical laboratory. National and international initiatives already use these principles to broaden access to science learning. India's Virtual Labs initiative explicitly targets gaps in laboratory facilities, while UNESCO-supported digital science resources demonstrate the growing policy importance of accessible virtual experimentation.

The central conclusion of this study, however, is that virtual laboratory availability should not be mistaken for virtual laboratory equity. Equity requires attention to bandwidth, devices, disability accessibility, language, digital literacy, instructor capability, cost, repeatability, and practical-skill transfer. A student who technically has access to a platform but cannot afford sufficient data, use its interface with assistive technology, or connect from an available device has not received an equivalent laboratory opportunity.

The simulated comparison therefore favors an equity-optimized hybrid model rather than either an entirely conventional laboratory or an entirely cloud-dependent model. The proposed architecture uses virtual laboratories for repetition, conceptual exploration, pre-laboratory preparation, and access expansion while reserving scarce physical laboratory sessions for real instrumentation, safety, troubleshooting, measurement uncertainty, and material interaction. This position is consistent with current evidence indicating that virtual laboratories can support meaningful learning but do not universally replace hands-on laboratory experiences.

Future empirical research should evaluate this model in low-resource universities, rural colleges, community science programs, and institutions serving students with diverse accessibility needs. Research should measure not only test performance but also participation rates, bandwidth consumption, completion equity, disability accessibility, physical-skill transfer, instructor workload, cost per learner, and long-term science retention. The most equitable virtual laboratory will not necessarily be the most immersive or technologically complex. It will be the laboratory system that gives the largest and most diverse group of learners a credible opportunity to investigate scientific phenomena and to progress from virtual understanding to authentic experimental competence.

References

1. Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, *95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002.
2. Heradio, R., de la Torre, L., Galan, D., Cabrerizo, F. J., Herrera-Viedma, E., & Dormido, S. (2016). Virtual and remote labs in education: A bibliometric analysis. *Computers & Education, 98*, 14–38. https://doi.org/10.1016/j.compedu.2016.03.010.
3. Grout, I. (2017). Remote laboratories as a means to widen participation in STEM education. *Education Sciences, 7*(4), 85. https://doi.org/10.3390/educsci7040085.
4. Hawkins, I., & Phelps, A. J. (2013). Virtual laboratory vs. traditional laboratory: Which is more effective for teaching electrochemistry? *Chemistry Education Research and Practice, 14*, 516–523. https://doi.org/10.1039/C3RP00070B.
5. Wolf, T. (2010). Assessing student learning in a virtual laboratory environment. *IEEE Transactions on Education*, *53*(2), 216–222.
6. Feisel, L. D., & Rosa, A. J. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*, *94*(1), 121–130.
7. de Jong, T., Sotiriou, S., & Gillet, D. (2014). Innovations in STEM education: The Go-Lab federation of online labs. *Smart Learning Environments*, *1*, 3. https://doi.org/10.1186/s40561-014-0003-6.
8. Tatli, Z., & Ayas, A. (2012). Virtual chemistry laboratory: Effect of constructivist learning environment. *Turkish Online Journal of Distance Education, 13*(1), 183–199.
9. Herga, N. R., & Dinevski, D. (2012). Virtual laboratory in chemistry—Experimental study of understanding, reproduction and application of acquired knowledge of subject's chemical content. *Organizacija*, *45*(3), 108–116.
10. Naumenko, O. M. (2012). Virtual chemical laboratory as constituent of the Internet-oriented pedagogical technology. *Information Technologies and Learning Tools, 31*(5). https://doi.org/10.33407/itlt.v31i5.728.
11. Hawkins, I. C. (2013). *Virtual laboratory versus traditional laboratory: Which is more effective for teaching electrochemistry?* [Doctoral dissertation, Middle Tennessee State University].
12. Herga, N. R., Grmek, M. I., & Dinevski, D. (2014). Virtual laboratory as an element of visualization when teaching chemical contents in science class. *Turkish Online Journal of Educational Technology*, *13*(4), 157–165.
13. Chiu, J. L., DeJaegher, C. J., & Chao, J. (2015). The effects of augmented virtual science laboratories on middle school students' understanding of gas properties. *Computers & Education, 85*, 59–73. https://doi.org/10.1016/j.compedu.2015.02.007.
14. Rosado, L., & Herreros, J. R. (2005). New experiences with remote laboratories in physics education. *International Journal of Engineering Education, 21*(4), 617–623.
15. García-Zubía, J., & Alves, G. R. (Eds.). (2011). *Using Remote Labs in Education: Two Little Ducks in Remote Experimentation*. University of Deusto.

16. Lindsay, E. D., Liu, D., Murray, S., & Bright, C. (2011). Remote laboratories: Enabling access to science and engineering experiments. *Proceedings of the 2011 IEEE Global Engineering Education Conference*, 1–6.
17. Tho, S. W., & Yeung, Y. Y. (2014). Remote laboratory system for technology-enhanced science learning: The design and pilot implementation in undergraduate courses. *Proceedings of the 22nd International Conference on Computers in Education*.
18. Dyrberg, N. R., Treusch, A. H., & Wiegand, C. (2017). Virtual laboratories in science education: Students' motivation and experiences in two tertiary biology courses. *Journal of Biological Education*, *51*(4), 358–374. https://doi.org/10.1080/00219266.2016.1257498.
19. Husnaini, S. J., & Chen, S. (2019). Effects of guided inquiry virtual and physical laboratories on conceptual understanding, inquiry performance, scientific inquiry self-efficacy, and enjoyment. *Physical Review Physics Education Research*, *15*(1), 010119. https://doi.org/10.1103/PhysRevPhysEducRes.15.010119.
20. Penn, M., & Ramnarain, U. (2019). A comparative analysis of virtual and traditional laboratory chemistry learning. *Perspectives in Education*, *37*(2), 80–97.