VIRTUAL LABORATORIES AND SCIENCE LEARNING: A META-ANALYSIS OF THEIR EDUCATIONAL EFFECTIVENESS

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ABSTRACT
The increasing use of digital technologies in education has considerably changed the ways in which students encounter scientific experimentation. Among these developments, virtual laboratories have received particular attention because they can simulate experimental environments, provide repeated opportunities for investigation, reduce dependence on physical equipment, and permit students to explore scientific phenomena that may otherwise be difficult to reproduce in school laboratories. At the same time, the educational value of virtual laboratories cannot be understood simply in terms of their technological sophistication. Questions concerning learning effectiveness, practical engagement, conceptual understanding, student attitudes, instructional support, and the relationship between virtual and physical experimentation remain important. The present paper synthesizes findings from empirical reviews, systematic reviews, and meta-analyses examining virtual, remote, physical, and blended laboratory experiences in science education. The paper provides a meta-analytic synthesis of existing evidence and organizes the literature according to recurring patterns of findings. The evidence indicates that virtual laboratories can produce learning outcomes comparable to those associated with conventional hands-on laboratories and, under particular instructional conditions, may produce higher achievement in specific areas of science learning. However, the evidence does not support a universal conclusion that virtual laboratories should replace physical laboratories. Outcomes appear to depend on the learning objective, subject area, instructional design, level of guidance, duration of intervention, learner characteristics, and opportunities for interaction with teachers and peers. Recent research also suggests that combining virtual and physical experimentation supports a complementary rather than replacement-oriented view of virtual laboratories and identifies important directions for future empirical research, particularly at the secondary-school level.

Keywords: *virtual laboratory, physical laboratory, science education, laboratory learning, virtual experimentation, hands-on learning, meta-analysis, systematic review*

INTRODUCTION

Laboratory experiments has traditionally occupied an important position in science education because science is not learned only through reading or listening. Students are expected to observe phenomena, manipulate materials, make measurements, formulate explanations, interpret evidence, and connect theoretical ideas with observable events. The laboratory therefore provides an environment in which scientific knowledge can be experienced rather than merely described. Physical laboratories require appropriate infrastructure, apparatus, consumable materials, maintenance, safety arrangements, adequate time, and teachers who are sufficiently prepared to organize experimental activities. These requirements can be particularly challenging in schools where laboratory resources are limited. Such circumstances have contributed to growing interest in virtual and remote laboratory environments.

Virtual laboratories generally provide computer-based representations of experimental equipment, materials, procedures, and phenomena. Students can manipulate variables, observe simulated outcomes, repeat procedures, and sometimes receive immediate feedback. Remote laboratories differ in that students interact through digital interfaces with actual experimental equipment located elsewhere. Although the two approaches are technologically related, they should not automatically be treated as identical educational experiences.

Brinson's review of empirical comparative research found that non-traditional laboratories, including virtual and remote laboratories, frequently produced learning outcomes equal to or greater than those obtained through traditional hands-on laboratories. At the same time, the review revealed a strong concentration on knowledge and understanding outcomes, with comparatively fewer investigations of practical, inquiry, analytical, and communication skills.

Subsequent meta-analyses have strengthened the evidence for the educational potential of virtual laboratories. Santos and Prudente (2022), for example, reported a medium overall effect ($g = 0.587$) favouring virtual laboratory activities in student achievement. Antonio and Castro (2023), focusing specifically on secondary-school physics, reported a larger overall effect ($g = 0.941$) for virtual simulations. However, other evidence is more cautious. Muilwijk and Lazonder (2023), after synthesizing 35 studies comparing physical and virtual investigations, did not find a statistically significant overall difference in conceptual knowledge acquisition between the two approaches.

The purpose of the present paper is therefore not to declare one laboratory format universally superior. Instead, it synthesizes the existing evidence, identifies areas of convergence and disagreement, and considers what the accumulated literature implies for the future use of virtual laboratories in science education.

CONCEPTUALISING VIRTUAL LABORATORIES

A virtual laboratory is understood as a digitally mediated environment that allows learners to conduct or simulate scientific experiments without directly manipulating the corresponding physical apparatus. Depending on the technology,

virtual laboratories include two-dimensional simulations, three-dimensional environments, interactive animations, computer-based experiments, immersive virtual reality, or other forms of digital experimentation.

Chan et al. (2021), in their systematic review of virtual chemical laboratories, reported that virtual laboratories generally produced better cognitive outcomes than passive forms of learning and produce outcomes equal to or greater than those of hands-on laboratories. However, they also identified weaknesses in the existing literature, including limited attention to learning theory, instructional support, and skill-based outcomes.

This observation is important because a virtual laboratory should not be equated with simply watching an animated demonstration. Meaningful experimentation requires learners to make decisions, manipulate variables, interpret results, and construct explanations. Consequently, the pedagogical design surrounding the technology is likely to be at least as important as the technology itself.

METHODOLOGICAL FRAMEWORK

The present paper adopts a meta-analytic synthesis approach. Instead. It brings together findings reported in existing systematic reviews, empirical reviews, and meta-analyses and organizes them according to recurring patterns in the evidence. The literature was therefore examined according to several broad questions:

1. Do virtual laboratories produce learning outcomes comparable to physical laboratories?
2. Under what circumstances have virtual laboratories demonstrated positive effects?
3. What evidence exists for combining virtual and physical laboratory experiences?
4. What limitations have been identified?
5. What evidence exists concerning affective outcomes?
6. Which instructional and learner-related factors appear to influence effectiveness?

FINDINGS OF THE META-ANALYSIS

1 Virtual Laboratories Can Produce Outcomes Comparable to Physical Laboratories

One of the most consistent findings in the literature is that virtual laboratories are capable of supporting learning outcomes comparable to those obtained through conventional laboratory experiences.

Brinson (2015) reviewed empirical studies that directly compared traditional hands-on laboratories with virtual and remote laboratory environments. The review found evidence that students using non-traditional laboratories achieve outcomes equal to or greater than those achieved through traditional laboratory instruction. Most of the studies concentrated on knowledge and understanding rather than practical or experimental skills.

A similar conclusion emerged from the second-order systematic review conducted by Fadda, Salis, and Vivanet (2022). Their review synthesized nine systematic reviews and one meta-analysis focusing on virtual and remote laboratories in secondary-school STEM education. They concluded that online laboratories supported learning at levels comparable to real laboratories. Their analysis further suggested that the educational contribution of online laboratories was particularly promising when they were integrated into conventional instruction, such as being used before hands-on laboratory work, and when students received appropriate teacher feedback.

This evidence challenges the assumption that learning necessarily suffers when students move from physical apparatus to digital representations. At the same time, equivalence in academic outcomes should not be interpreted as equivalence in every aspect of laboratory experience. A student may demonstrate similar conceptual knowledge after a virtual experiment while having a different level of experience with actual equipment, materials, measurement procedures, or physical manipulation. Thus, it is evident that that virtual laboratories support learning effectively, rather than for the proposition that they are identical substitutes for physical laboratory experiences.

2. Studies related to Positive Effects on Academic Achievement

A second group of studies reports outcomes that favour virtual laboratory experiences. Santos and Prudente (2022) conducted a meta-analysis of virtual laboratory activities in science education and reported an overall medium effect size of $g = 0.587$ in favour of virtual laboratories for student achievement. The authors also examined subject area and educational level as subgroup variables, indicating that the effectiveness of virtual laboratories cannot necessarily be assumed to be identical across all contexts.

Specifically, Antonio and Castro (2023) conducted a meta-analysis of virtual simulations and secondary students' achievement in physics. Their synthesis included 15 studies and yielded an overall Hedges' g of 0.941, indicating a large positive effect.

The findings of Syahwin, Hardianti, and Fitriana (2022) in their meta-analysis examined guided inquiry learning supported by virtual laboratories in Indonesian Senior High-School Physics. Twenty-four eligible studies were included, and the overall effect size was reported as Hedges' $g = 0.94$.

These studies suggest that virtual laboratory environments can contribute meaningfully to academic achievement, particularly when they are embedded within structured instructional approaches such as guided inquiry. The studies differ in their inclusion criteria, subject domains, outcome measures, populations, and experimental conditions. Consequently, the numerical values provide evidence of magnitude within particular syntheses rather than a single universal estimate of virtual laboratory effectiveness.

3 Inconsistently in evidences favouring Virtual Laboratories

Muilwijk and Lazonder (2023) conducted a meta-analysis of 35 studies comparing physical and virtual investigations in relation to conceptual knowledge acquisition. Their analysis was designed specifically to examine whether the physicality of experimental materials affected learning. The overall evidence did not establish a statistically significant

advantage for physical or virtual investigation across the complete set of studies. Zacharia and Constantinou (2008) found no significant difference between physical and virtual manipulatives in students' conceptual understanding and inquiry-related learning in physics. Brinson (2017) likewise reported that both physical and virtual laboratory groups improved their understanding of density, but the difference between the two groups was not statistically significant. These finding is particularly important for interpreting the broader literature.

4 Evidence for Blending Virtual and Physical Laboratories

An important development in the literature is the movement away from treating virtual and physical laboratories as mutually exclusive alternatives.

Flegr, Fabian, and Futterer (2026) conducted a meta-analysis involving 25 articles, 41 effect sizes, and 2,955 school and university students. Their results indicated that combining real and virtual experiments significantly enhanced conceptual understanding, with an overall effect size of 0.71

Olympiou and Zacharia (2012) compared physical manipulatives, virtual manipulatives, and a deliberately blended combination of the two in an inquiry-oriented learning environment. Their study involved 70 undergraduate students studying light and colour. The blended condition produced greater conceptual understanding than either physical or virtual experimentation alone.

5. **Evidence Concerning Practical and Experimental Skills**

Fadda et al. (2022) found that content knowledge was the outcome frequently assessed in the secondary-school literature, whereas practical and inquiry skills were investigated less frequently. Chan et al. (2021) similarly identified a lack of research concerning skill-based outcomes in virtual chemical laboratories. Consequently, achievement tests alone doesn't provide a complete evaluation of laboratory effectiveness. For research concerning secondary-school science education, experimental skill deserves more systematic attention. Skill assessment may include areas such as:

- identifying and selecting appropriate apparatus;
- following experimental procedures;
- handling materials and equipment;
- measuring accurately;
- recording observations systematically;
- controlling experimental variables;
- interpreting experimental error;
- drawing evidence-based conclusions; and
- demonstrating safe and responsible laboratory practices.

6.Affecive Outcomes, Attitudes and Self-Efficacy

The literature related to examining outcomes beyond academic achievement were also found. Putica and Stanišić (2025) conducted a meta-analysis of 22 quasi-experimental studies examining affective learning outcomes in natural-science laboratory work. Their results indicated statistically significant positive effect for virtual laboratory work compared with hands-on laboratory work.

Swastika, Gupta, and Abuhasan (2024) similarly examined scientific attitude and self-efficacy. Their meta-analysis reported that 58% of the studies they reviewed found virtual laboratories more effective for scientific attitude, while 64% reported stronger outcomes for self-efficacy compared with physical laboratory activities.

These findings suggest that students' reactions to laboratory environments are an important dimension of effectiveness. Students may value virtual environments because they allow repeated attempts, reduce anxiety associated with making mistakes, and provide immediate visual feedback. Nevertheless, affective responses should not be interpreted as evidence that one laboratory format is universally preferable. Student enjoyment, confidence, motivation, and perceived usefulness are influenced by instructional context as well as technological characteristics.

MAJOR RESEARCH GAP

The synthesis of existing evidence reveals several areas in which further research is warranted. First, the literature is dominated by cognitive outcomes, particularly academic achievement and conceptual understanding. Brinson (2015), Fadda et al. (2022), and Chan et al. (2021) all point, directly or indirectly, to the relative scarcity of research on practical and inquiry-related outcomes. Relatively less attention has been given to long-term retention. Immediate post-tests determines whether students learned something immediately after an intervention, but it is not establish whether that knowledge remains accessible after a period without instruction. Delayed assessment is therefore important when comparing laboratory environments.

Experimental skills remain insufficiently represented in the literature. A laboratory is not merely a medium for acquiring factual knowledge but it is a place in which learners develop procedural competence, measurement skills, observation skills, and the ability to deal with experimental uncertainty.

Many studies investigate only one outcome at a time. A laboratory intervention may influence academic achievement, practical performance, retention, and student reaction in different ways. Examining these outcomes together therefore provide a more complete understanding of laboratory effectiveness. Methodological heterogeneity makes direct comparison difficult. Virtual laboratories differ considerably in technology, level of interactivity, degree of realism, instructional guidance, duration, and subject matter. Consequently, the term "virtual laboratory" covers a diverse range of educational interventions.

There is a need for more evidence from specific national and educational contexts. Findings obtained in one country or

educational system is not automatically generalized to another because laboratory infrastructure, curriculum requirements, teacher preparation, class size, digital access, and students' prior technological experience may differ.

IMPLICATIONS FOR SCIENCE EDUCATION

The accumulated evidence suggests several implications for science educators and researchers as follows-

1. Virtual laboratories acts as instructional environments rather than merely technological substitutes. Their effectiveness depends on their incorporation into the teaching-learning process.
2. Virtual experimentation is particularly valuable for preparatory activities. Students become familiar with concepts, apparatus, procedures, and variables before undertaking physical experiments. Such preparation may allow valuable laboratory time to be used more efficiently.
3. Physical laboratory work continues to have educational importance. Direct interaction with materials and instruments provides experiences that cannot always be represented completely through simulation. Therefore, evidence supporting virtual laboratories should not be interpreted as evidence that physical laboratories have become unnecessary.
4. Blended laboratory designs deserve greater attention. Evidence from both individual studies and recent meta-analysis suggests that combining real and virtual experimentation may provide complementary learning opportunities.
5. Future evaluations should use broader outcome measures. Academic achievement alone is insufficient to represent the full educational contribution of laboratory work. Measures of experimental skill, conceptual understanding, retention, scientific attitude, self-efficacy, motivation, and student reaction can provide a more comprehensive picture.

CONCLUSION

The studies synthesized in this paper indicates that virtual laboratories have established themselves as a credible component of contemporary science education. Across reviews and meta-analyses, virtual laboratory experiences have frequently produced learning outcomes comparable to physical laboratory experiences, while several meta-analyses have reported statistically significant positive effects in particular educational contexts.

Evidence from comparative meta-analysis demonstrates that difference is small or statistically non-significant when conceptual knowledge is considered across diverse studies. The effectiveness of a laboratory environment appears to depend substantially on the learning objective, subject matter, instructional design, teacher support, learner characteristics, and nature of the experimental activity.

The strongest direction emerging from the literature reviews therefore not replacement but purposeful integration of Virtual and Physical Lab. Virtual laboratories provide opportunities for repeated experimentation, visualisation, preparation, exploration, and conceptual development, while physical laboratories provide direct experience with equipment, materials, measurement, and real experimental conditions. Their integration produces a richer learning experience than treating either as an exclusive alternative.

Most of the existing literature has concentrated on academic achievement and conceptual knowledge, while experimental skills, long-term retention, inquiry processes, and other learner responses remain comparatively under-investigated. This limitation provides a strong rationale for future research that examines multiple dimensions of learning within the same experimental design.

Therefore, the future of laboratory-based Science Education need not be understood as a choice between the physical and the Virtual Lab. The relevant research question is how each environment can be designed and used to support particular educational purposes. A rigorous comparison of virtual and physical laboratory experiences, particularly among secondary-school students and across cognitive, practical, retention, and affective outcomes, can therefore make a meaningful contribution to the growing evidence base in science education.

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