

INTEGRATION OF ARTIFICIAL INTELLIGENCE-DRIVEN VIRTUAL LABS IN TEACHING CHEMISTRY IN SECONDARY SCHOOLS

Ezenwa Ekwe

Department of Chemistry Education, Enugu State College of Education Technical, Enugu

Corresponding author: Ezenwa Ekwe

ABSTRACT

The teaching of chemistry in secondary schools has long grappled with constraints in laboratory access, safety concerns, resource inadequacy, and low student motivation. Artificial intelligence (AI)-driven virtual laboratories offer a transformative solution by providing immersive, interactive, and adaptive digital environments that replicate or augment physical laboratory experiences. This paper examines the conceptual foundations, pedagogical merits, and implementation challenges of integrating AI-driven virtual labs into secondary school chemistry instruction. Drawing on a systematic review of empirical studies, theoretical frameworks, and platform analyses published between 2010 and 2024, the paper demonstrates that AI-driven virtual labs significantly improve students' conceptual understanding, practical skills, engagement, and academic performance in chemistry. Barriers including digital infrastructure deficits, teacher competency gaps, and curriculum misalignment, particularly in developing-country contexts such as Nigeria are critically appraised. The paper recommends a hybrid laboratory model, targeted teacher professional development, stakeholder policy advocacy, and phased integration strategies as pathways toward equitable and effective adoption. Implications for curriculum design and future research are discussed.

Keywords: Artificial Intelligence; Virtual Laboratories; Chemistry Education; Secondary Schools; Technology Integration; Nigeria

1. Introduction

Chemistry occupies a pivotal position in the secondary school science curriculum, serving as the intellectual bridge between the abstract laws of physics and the biological processes of life. Its mastery equips students with analytical reasoning, quantitative thinking, and laboratory competencies that are indispensable for STEM-based careers and national development. Yet, the global landscape of secondary school chemistry education is riddled with persistent pedagogical challenges. Insufficient laboratory facilities, inadequate chemical reagents, safety hazards, large class sizes, and demotivated learners collectively undermine the realisation of chemistry's educational promise (Hofstein & Lunetta, 2004; Abrahams & Millar, 2008).

In Nigeria, these challenges are acute. A significant proportion of public secondary schools lack functional laboratories, and where such facilities exist, they are often ill-equipped, outdated, or unsafe (Okeke & Abubakar, 2013). Consequently, many chemistry teachers resort to purely theoretical instruction, depriving students of the experimental inquiry that is central to scientific literacy. This has contributed to declining student performance in national examinations such as the West African Senior School Certificate Examination (WASSCE), where chemistry consistently records high failure rates (WAEC, 2023).

Against this backdrop, the emergence of artificial intelligence (AI)-driven virtual laboratories presents a compelling and timely pedagogical alternative. These are sophisticated digital platforms that simulate chemical laboratory environments with high fidelity, providing interactive experiments, real-time adaptive feedback, and personalised learning trajectories. Unlike static multimedia or simple simulation software, AI-driven virtual labs employ machine learning algorithms, natural language processing, and intelligent tutoring systems to create responsive educational experiences that adapt to individual learner needs (Makransky & Lilleholt, 2018).

This paper argues that the strategic integration of AI-driven virtual labs into secondary school chemistry instruction can address longstanding deficiencies in practical chemistry education, improve learning outcomes, and democratise access to quality science education. The paper proceeds as follows: Section 2 reviews the literature on virtual laboratories and AI in science education; Section 3 presents the theoretical framework underpinning the study; Section 4 analyses the benefits of AI-driven virtual labs; Section 5 examines implementation challenges; Section 6 proposes a framework for integration; Section 7 discusses implications; and Section 8 concludes the paper.

2. Literature Review

2.1 Evolution of Laboratory Instruction in Chemistry Education

The laboratory has been considered indispensable to chemistry education since the nineteenth century, when Justus von Liebig established the first formal teaching laboratory at the University of Giessen in 1824 (Bensaude-Vincent & Simon, 2008). Since then, laboratory work has been theorised as central to scientific inquiry, hypothesis testing, and the development of practical skills. Hofstein and Lunetta (2004), in their seminal review, identified laboratory activities as uniquely effective in fostering scientific thinking, collaborative skills, and intrinsic motivation, provided they are well-designed and purposefully integrated into instruction.

However, empirical research has increasingly questioned whether traditional laboratories consistently deliver on these promises. Abrahams and Millar (2008) found that while students are generally engaged during laboratory activities, the intended learning outcomes, particularly conceptual understanding, are often not achieved. This disconnect between laboratory activity and learning has prompted educators and researchers to explore technological alternatives that retain the experiential qualities of physical labs while addressing their structural limitations.

2.2 Virtual Laboratories in Science Education

Virtual laboratories digitally simulated environments that replicate the procedures, outcomes, and phenomena of physical experiments emerged as a significant pedagogical tool in the late 1990s and early 2000s, coinciding with the proliferation of internet-enabled computing in educational institutions. Early virtual labs were primarily web-based animations offering limited interactivity. Over time, they evolved into sophisticated, three-dimensional simulated environments offering

branching scenarios, variable manipulation, and data-collection capabilities (Dalgarno et al., 2009).

A considerable body of research has documented the effectiveness of virtual labs in science education. Ma and Nickerson (2006) conducted a meta-analysis of 33 studies comparing virtual, physical, and combined laboratory approaches. Their findings indicated that virtual laboratories produced learning outcomes comparable to, and in some cases superior to, physical laboratories, particularly for conceptual understanding and attitudinal measures. Tatli and Ayas (2013) found that Turkish secondary school students who used virtual chemistry labs outperformed their counterparts in traditional labs on assessments of particulate-level understanding of chemical reactions.

2.3 Artificial Intelligence in Education

The integration of artificial intelligence into educational technology has accelerated markedly since the mid-2010s, driven by advances in machine learning, natural language processing, and big data analytics. AI in education (AIED) encompasses a range of applications, including intelligent tutoring systems (ITS), automated assessment, learning analytics, adaptive learning platforms, and conversational agents (Baker & Siemens, 2014; Holmes et al., 2019).

Intelligent tutoring systems, first conceptualised by Carbonell (1970), are AI-powered programs that simulate one-on-one tutoring by modelling the learner's knowledge state, diagnosing misconceptions, and providing customised instructional feedback. Bloom's (1984) foundational study demonstrated that one-on-one tutoring produces learning gains two standard deviations above classroom instruction, a benchmark that ITS designers have long sought to replicate through automation. Contemporary ITS platforms, such as Carnegie Learning's MATHia and ALEKS, have demonstrated statistically significant improvements in student outcomes across subjects (Ritter et al., 2007).

2.4 AI-Driven Virtual Labs for Chemistry

The convergence of virtual laboratory technology and artificial intelligence has produced a new generation of AI-driven virtual chemistry labs that offer unprecedented pedagogical sophistication. Platforms such as Labster, PhET Interactive Simulations, ChemCollective, Vived Chemistry, and Smart Sparrow represent the current state of the art. These platforms employ AI algorithms to monitor learner behaviour in real time, diagnose errors, generate adaptive hints, adjust difficulty levels, and produce detailed analytics for instructors (Winkelmann et al., 2020).

Makransky et al. (2017) demonstrated in a randomized controlled study that students using AI-enhanced virtual lab environments exhibited significantly higher transfer of learning to novel problems compared with students in traditional lecture-based instruction. Olympiou and Zacharia (2012) found that blended laboratory approaches, combining physical and virtual labs, produced the most robust learning outcomes in chemistry. These findings collectively suggest that AI-driven virtual labs are not merely substitutes for physical labs but can serve as powerful supplements that extend and deepen chemistry learning.

3. Theoretical Framework

This paper is anchored in three complementary theoretical frameworks that collectively explain how and why AI-driven virtual labs may enhance chemistry learning in secondary schools.

3.1 Constructivism

Rooted in the intellectual traditions of Piaget (1970) and Vygotsky (1978), constructivism holds that learners actively construct knowledge through experience, reflection, and social interaction. Virtual laboratory environments are inherently constructivist in design: they present learners with scientific problems to investigate, provide manipulable variables, encourage hypothesis formulation, and offer feedback based on experimental outcomes. The AI layer augments constructivist learning by scaffolding learners through zones of proximal development, providing calibrated support that is neither too directive nor too minimal (Vygotsky, 1978).

3.2 Cognitive Load Theory

Sweller's (1988) Cognitive Load Theory (CLT) posits that effective instruction must manage the allocation of cognitive resources between intrinsic load (inherent task complexity), extraneous load (poorly designed instruction), and germane load (deep learning effort).

Traditional chemistry labs impose high extraneous cognitive load through procedural complexity, safety precautions, and physical equipment management. AI-driven virtual labs reduce extraneous load by automating procedural steps, providing guided walkthroughs, and eliminating safety concerns, thereby freeing cognitive resources for germane learning of chemical concepts (Makransky & Lilleholt, 2018).

3.3 Technology Acceptance Model

Davis's (1989) Technology Acceptance Model (TAM) proposes that users adopt technology based on their perceptions of its usefulness and ease of use. For AI-driven virtual labs to achieve widespread adoption in secondary school chemistry, they must be perceived by both teachers and students as pedagogically valuable and practically manageable. Research has consistently found that when teachers receive adequate training and institutional support, their TAM perceptions improve significantly, leading to sustained technology integration (Teo, 2011). This framework informs the implementation recommendations offered in Section 6 of this paper.

4. BENEFITS OF AI-DRIVEN VIRTUAL LABS IN SECONDARY SCHOOL CHEMISTRY

4.1 Enhanced Conceptual Understanding

One of the most robust findings in the literature is that AI-driven virtual labs significantly improve students' conceptual understanding of chemistry. The ability of virtual environments to visualise molecular-level phenomena, the movement of electrons, the formation of ionic bonds, and the dynamics of chemical equilibria addresses a well-documented barrier in chemistry learning: the difficulty of comprehending the sub-microscopic world (Johnstone, 1982). Rutten et al. (2012), in a meta-analysis of 47 studies, found a mean effect size of $d = 0.53$ favouring computer simulations over traditional instruction for conceptual learning in science.

AI-driven adaptive features amplify these gains by identifying specific conceptual gaps and tailoring explanatory content accordingly. When a student repeatedly makes errors in predicting reaction products, the AI system can redirect them to targeted mini-tutorials on electronegativity, electron configuration, or bonding theory, a level of individualised responsiveness impossible in a classroom of thirty students.

4.2 Development of Practical and Inquiry Skills

A persistent concern about virtual laboratories is whether they develop genuine practical competencies or merely simulate them. Contemporary AI-driven platforms have addressed this concern through increasingly sophisticated procedural simulations. Students in Labster environments, for instance, perform titrations by controlling pipette volumes, observing colour changes, and calculating molarity, procedural actions that mirror physical titration closely (Winkelmann et al., 2020). Research by Zacharia et al. (2008) found that students who completed virtual chemistry experiments prior to physical laboratory work demonstrated superior manipulative skills and experimental design abilities.

Inquiry-based features embedded in AI-driven virtual labs further develop higher-order scientific thinking. Students are challenged to formulate hypotheses, design experimental protocols, collect and analyse data, and draw conclusions, the full cycle of scientific inquiry. Pedaste et al. (2015) identified inquiry-based learning as among the most effective approaches to science education, and AI-driven virtual labs provide an ideal scaffolded environment for its implementation.

4.3 Improved Student Engagement and Motivation

The gamification elements, three-dimensional environments, and narrative contexts incorporated in modern AI-driven virtual labs have been found to substantially increase student motivation and engagement. Makransky et al. (2019) documented that secondary students using virtual reality-enhanced chemistry labs reported significantly higher levels of presence, enjoyment, and intrinsic motivation than with textbook instruction. These affective gains are not trivial: Hidi and Renninger's (2006) four-phase model of interest development identifies situational interests, sparked by novel, engaging stimuli, as the precursor to the development of sustained personal interest in a subject.

For Nigerian secondary school students, who frequently cite the abstract and unappealing nature of chemistry as a barrier to engagement (Eze & Akubugwo, 2014), the immersive qualities of AI-driven virtual labs may be particularly significant in transforming affective orientations toward the subject.

4.4 Safety and Resource Advantages

The safety benefits of virtual chemistry labs are considerable. Secondary school chemistry involves experiments with corrosive acids, flammable organic solvents, toxic heavy metal salts, and explosive compounds. Virtual environments eliminate the risk of chemical burns, fires, toxic inhalation, and equipment damage, thereby enabling students to conduct high-risk experiments without physical danger. This is especially salient in the Nigerian context, where the lack of safety equipment, fume hoods, fire extinguishers, and first-aid kits makes many experiments impractical or irresponsible in physical settings.

The cost advantages are equally significant. Once a virtual lab platform is acquired, its marginal cost per experiment approaches zero: reagents are never consumed, glassware is never broken, and apparatus never deteriorates. For cash-strapped public secondary schools, this financial model offers a transformative path to practical chemistry instruction without recurring supply expenditures.

4.5 Data-Driven Assessment and Analytics

AI-driven virtual labs generate rich streams of learning data, keystrokes, decision sequences, time-on-task, error patterns, and assessment scores that provide instructors with unprecedented insight into student learning processes. These learning analytics enable formative assessment at a granularity impossible in traditional settings. Rather than waiting for end-of-term examinations to identify struggling students, teachers can receive real-time dashboards indicating which students are misconceiving titration end-points, struggling with mole calculations, or bypassing procedural safety steps (Siemens, 2013).

The shift from summative to formative data-driven assessment aligns with current best practice in educational assessment (Black & Wiliam, 1998) and enables teachers to intervene proactively, differentiate instruction, and monitor progress over time.

Source: Author's synthesis from literature review (2024)

5. CHALLENGES AND BARRIERS TO IMPLEMENTATION

5.1 Digital Infrastructure Deficit

Table 1: Comparison of Traditional Physical Labs and AI-Driven Virtual Labs in Secondary Chemistry

Feature	Traditional Lab	AI-Driven Virtual Lab
Safety	Chemical hazards present	Zero physical risk
Cost	High reagent/equipment cost	One-time software investment
Access	Limited to school hours	24/7 anywhere availability
Feedback	Delayed/teacher-dependent	Instant AI-generated feedback
Repetition	Constrained by materials	Unlimited repetitions
Adaptivity	Uniform instruction	Personalised learning paths
Collaboration	Physical co-presence required	Global remote collaboration

The most formidable barrier to AI-driven virtual lab integration in Nigerian secondary schools is the inadequacy of digital infrastructure. Functioning computers, reliable electricity supply, high-speed internet connectivity, and device maintenance systems are prerequisites for virtual lab deployment that remain unevenly distributed across the country. The Nigerian National Bureau of Statistics (2022) reported that fewer than 35% of public secondary schools have functional computer laboratories, and consistent electricity supply, even with alternative sources, is a significant challenge in many states.

This digital divide risks exacerbating existing educational inequalities between urban elite schools and rural public schools. Any integration framework must therefore include explicit provisions for infrastructure development or offline-capable virtual lab solutions.

5.2 Teacher Competency and Training Gaps

The effectiveness of any educational technology depends critically on the pedagogical competence of the teachers who deploy it. Many Nigerian secondary school chemistry teachers lack both the technical skills to operate AI-driven platforms and the pedagogical knowledge to integrate them effectively into inquiry-based instruction. Usman and Abubakar (2018) found that the majority of secondary school science teachers in northern Nigeria had never used any form of virtual laboratory software, and fewer than 20% had received technology-integration training in their pre-service or in-service education.

This training gap is compounded by the limited availability of localised technical support and the occasional unreliability of vendor-provided tutorials. Professional development programmes must be contextually designed, practically focused, and sustained over time to produce meaningful change in teacher practice.

5.3 Curriculum and Assessment Misalignment

Secondary school chemistry curricula in Nigeria, governed by the Nigeria Educational Research and Development Council (NERDC), were not designed with AI-driven virtual labs in mind. As a result, the experiments prescribed in the practical chemistry syllabus may not correspond exactly to the modules available in commercial virtual lab platforms. This misalignment creates implementation friction: teachers may find it difficult to justify time spent on virtual experiments that do not directly map to externally assessed practical skills.

Furthermore, examination bodies such as WAEC and NECO continue to assess chemistry practical skills through physical laboratory performance. Until assessment frameworks are updated to recognize and incorporate virtual laboratory competencies, teachers face structural disincentives to invest instructional time in AI-driven virtual labs.

5.4 Socio-Economic and Equity Considerations

Commercial AI-driven virtual lab platforms typically require subscription fees that may be prohibitive for individual schools or school boards. Although open-source alternatives such as PhET simulations are freely available, they offer more limited AI-adaptive features. The reliance on personal devices or school computers also introduces equity concerns in schools where students do not have home access to computing devices, limiting after-hours practice and independent exploration.

5.5 Student Digital Literacy and Attitudinal Barriers

Students' ability to benefit from AI-driven virtual labs depends on their baseline digital literacy, their comfort and proficiency with computing devices, software navigation, and digital communication. Where digital literacy is low, students may expend cognitive resources on interface navigation rather than chemistry learning a form of extraneous cognitive

load that diminishes the platform's educational value. Additionally, some students and parents may perceive virtual labs as inferior substitutes for 'real' laboratory work, reflecting cultural attitudes toward practical chemistry that may require deliberate attitudinal change interventions.

Source: Author's review of platform documentation and empirical literature (2026)

6. A FRAMEWORK FOR INTEGRATING AI-DRIVEN VIRTUAL LABS IN NIGERIAN SECONDARY SCHOOLS

Table 2: Selected AI-Driven Virtual Chemistry Lab Platforms and Evidence of Effectiveness

Platform	AI Features	Chemistry Modules	Notable Finding
Labster	Adaptive quizzes, hint engine	Titrations, reactions, stoichiometry	22% higher test scores (Winkelmann et al., 2020)
PhET Simulations	Guided discovery AI	Molecules, reactions, states of matter	Improved conceptual understanding (Perkins et al., 2012)
ChemCollective	Scenario-based tutoring	Solution preparation, equilibrium	Enhanced problem-solving skills (Yaron et al., 2010)
Vived Chemistry	3D molecular AI rendering	Organic chemistry, bonding	Spatial visualisation gains (Merchant et al., 2013)
Smart Sparrow	Adaptive e-learning engine	General secondary chemistry	Reduced learning time by 34% (Pappas, 2015)

Drawing on the empirical literature, theoretical frameworks, and contextual analysis presented above, this paper proposes a five-component integration framework tailored to the Nigerian secondary school context.

6.1 Infrastructure Development and Platform Selection

Schools should conduct an audit of existing digital infrastructure and develop a phased plan for upgrading computing facilities, ensuring reliable power supply (including solar backup systems), and establishing internet connectivity. Platform selection should prioritise solutions that offer offline functionality, are available in low-bandwidth versions, provide locally relevant chemistry content, and offer affordable or subsidised pricing for educational institutions in developing countries. Collaboration with state ministries of education and development partners such as UNICEF and the World Bank could provide funding support for infrastructure development.

6.2 Curriculum Mapping and Syllabus Integration

Chemistry education specialists, curriculum developers, and virtual lab platform providers should collaborate to map available virtual experiments onto the NERDC chemistry syllabus. This mapping exercise should identify which practical activities in the syllabus have direct virtual equivalents, which can be adapted, and which require supplementary traditional approaches. The resulting curriculum integration guide should specify where virtual labs serve as preparation for physical experiments, as supplements, or as substitutes where physical labs are unavailable.

6.3 Teacher Professional Development

A sustained, context-sensitive professional development programme is essential. This programme should encompass three phases. First, foundational technical training covering platform navigation, experiment facilitation, and analytics interpretation. Second, pedagogical training on inquiry-based instruction, formative assessment, and differentiated teaching using virtual lab data. Third, ongoing collaborative professional learning communities where chemistry teachers share integration strategies, troubleshoot challenges, and co-develop contextually relevant lesson plans. Training should be delivered through a combination of face-to-face workshops, online modules, and peer mentoring.

6.4 Hybrid Laboratory Model Implementation

A hybrid model that strategically combines AI-driven virtual labs and physical laboratory work is recommended as the optimal implementation approach. In this model, virtual labs serve as pre-laboratory preparation environments, helping students build conceptual understanding, rehearse procedures, and anticipate experimental outcomes before physical laboratory sessions. Post-laboratory, virtual environments support reflection, error analysis, and conceptual consolidation. For schools with very limited physical laboratory resources, virtual labs may serve as primary practical learning environments supplemented by occasional physical demonstrations.

6.5 Policy Advocacy and Stakeholder Engagement

Systemic integration requires policy-level change. Chemistry educators, teacher educators, and professional associations should advocate for the inclusion of virtual laboratory competencies in chemistry practical assessment frameworks, the provision of government funding for educational technology infrastructure, and the development of a national policy on AI in education. Stakeholder engagement with parents, school administrators, examination bodies, and government officials is essential to build the broad-based support necessary for sustainable institutional change.

7. Discussion And Implications

The evidence reviewed in this paper converges on a compelling conclusion: AI-driven virtual laboratories represent not merely a technological novelty but a pedagogically substantive innovation with the potential to transform chemistry education in secondary schools. Their ability to visualise the sub-microscopic world, provide adaptive feedback, eliminate safety risks, generate learning analytics, and expand

access to practical chemistry aligns directly with the core challenges of chemistry instruction documented in the Nigerian and international literature.

However, the paper's analysis equally underscores that technology alone does not determine educational outcomes. The effectiveness of AI-driven virtual labs is contingent on the quality of their pedagogical design, the competence of the teachers who deploy them, the adequacy of the supporting infrastructure, and the alignment of assessment systems. Plug-and-play technology adoption without these enabling conditions risks reproducing the limitations of traditional instruction in digital form.

For Nigerian secondary schools specifically, the implications are significant. The country's persistent laboratory infrastructure deficit, examination-driven curriculum, and uneven teacher professional development create both a strong rationale and a complex implementation landscape for AI-driven virtual labs. The framework proposed in Section 6 offers a structured approach that acknowledges these contextual realities while charting a pragmatic path toward integration.

For curriculum developers, the findings suggest a need to revise chemistry practical syllabuses to explicitly accommodate virtual laboratory competencies and to work with examination bodies to develop assessment instruments that recognize digital practical skills. For teacher educators at institutions such as Enugu State College of Education Technical, the paper highlights the urgency of incorporating AI-driven virtual lab training into pre-service chemistry teacher education programmes, equipping the next generation of teachers with the skills to leverage these technologies effectively from day one of their professional lives.

For researchers, several important questions remain unanswered. Longitudinal studies examining the sustained impact of AI-driven virtual lab use on chemistry achievement, practical skills retention, and career aspirations are notably absent from the literature. Context-specific studies examining implementation in Nigerian and other sub-Saharan African schools are limited, and more research is needed on the equity implications of different access models. The development and validation of assessment tools specifically designed to measure virtual laboratory competencies represents another significant research priority.

8. Conclusion

This paper has examined the integration of AI-driven virtual laboratories in secondary school chemistry education, with particular attention to the Nigerian educational context. Through a systematic review of theoretical frameworks and empirical studies, the paper has demonstrated that AI-driven virtual labs offer significant advantages in conceptual understanding, practical skills development, student engagement, safety, cost-effectiveness, and data-driven assessment. These benefits are particularly relevant to secondary schools in developing countries where laboratory infrastructure deficits constitute a severe constraint on practical chemistry instruction.

At the same time, the paper has critically examined the barriers to implementation: digital infrastructure gaps, teacher competency deficits, curriculum misalignment, equity concerns, and attitudinal challenges, and proposed a five-component integration framework that addresses these barriers in a contextually grounded manner. The framework advocates a hybrid laboratory model sustained by teacher professional development, curriculum mapping, infrastructure investment, and policy advocacy as complementary pillars of effective integration.

Chemistry education has a dual mandate: to develop scientific literacy in all students and to nurture the next generation of scientists, engineers, pharmacists, and environmental managers who will drive Nigeria's and Africa's development. AI-driven virtual labs, thoughtfully integrated into a broader pedagogical strategy, offer a powerful means of fulfilling this mandate, extending the reach of quality chemistry education to students regardless of the physical resources available in their schools. The question is no longer whether AI-driven virtual labs have pedagogical value; it is whether educators, policymakers, and institutions have the vision and commitment to harness that value for the benefit of all secondary school chemistry students.

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