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HARNESSING VIRTUAL LABORATORIES FOR EFFECTIVE CHEMISTRY TEACHING IN NIGERIAN SECONDARY SCHOOLS: ISSUES AND PROSPECTS

FESTUS-HART, Tina Omolola [1]
Science Education Department, Faculty of Education,
Ignatius Ajuru University of Education

WACHUKWU, Confidence [2]
Educational Technology Department, Faculty of Education,
Ignatius Ajuru University of Education

Abstract

Practical laboratory activities are fundamental to effective chemistry education; however, many Nigerian secondary schools face persistent challenges related to inadequate laboratory facilities, high costs of consumables, safety concerns, and limited instructional time. These constraints have contributed to students' persistent underachievement in chemistry, particularly in practical examinations. This position paper critically examines the challenges and prospects of integrating virtual laboratories into chemistry teaching in Nigerian secondary schools. Drawing on empirical studies, national examination reports, and policy documents, the paper identifies key barriers to adoption, including weak ICT infrastructure, insufficient teacher digital competence, high initial implementation costs, curriculum misalignment, and unequal access to digital resources. Despite these challenges, virtual laboratories present significant opportunities for improving student engagement, enhancing conceptual understanding, promoting safe and cost-effective experimentation, and expanding access to practical learning experiences. The paper argues that virtual laboratories should be adopted as complementary instructional media rather than substitutes for physical laboratories. Strategic recommendations are proposed, including targeted government investment, systematic teacher professional development, curriculum integration, public–private partnerships, and continuous monitoring and evaluation. The paper concludes that the thoughtful integration of virtual laboratories can help bridge existing gaps in chemistry education and support more equitable and effective science learning across Nigerian secondary schools.

Keywords: Virtual Laboratories, Chemistry, Students, Practical, Secondary Schools, Instructional Media, ICT Integration, Nigeria

Introduction

Chemistry education occupies a central position in science education due to its role in preparing learners for careers in medicine, engineering, pharmacy, environmental science, and other science-based professions that drive national development. As a discipline, chemistry involves abstract concepts such as atomic structure, molecular interactions, and chemical transformations, which often require practical experimentation to support conceptual understanding. Laboratory activities therefore serve as a critical bridge between theory and practice, enabling learners to develop psychomotor skills, scientific reasoning, and problem-solving abilities.

Traditionally, hands-on laboratory experiments have been regarded as the most effective approach to teaching chemistry, as they promote active learning, creativity, and observational skills (Musengimana et al., 2021). However, in many Nigerian secondary schools, effective laboratory instruction remains difficult to achieve. Inadequate laboratory facilities, overcrowded classrooms, irregular electricity supply, safety concerns, and the rising cost of chemical reagents have significantly constrained practical chemistry teaching. As a result, teachers often resort to theoretical explanations or demonstrations, limiting students' opportunities for meaningful experimental engagement and reinforcing the perception of chemistry as an abstract and difficult subject (Ali & Ullah, 2020).

National examination reports further highlight the consequences of these challenges. Persistent poor performance in chemistry practical examinations in the Senior School Certificate Examination (SSCE) suggests that many students lack essential practical competencies (Amba & Chinwendu, 2015; National Examinations Council [NECO], 2017). Similarly, the West African Examinations Council (WAEC, 2023) reported low mean scores in chemistry practical papers, indicating weaknesses in students' experimental skills and procedural understanding. These trends underscore the urgent need for alternative and complementary approaches to practical chemistry instruction.

In response to these challenges, virtual laboratories (VLs) have emerged globally as innovative instructional media capable of supporting practical science learning in resource-constrained contexts. Virtual laboratories are computer-based environments that simulate real laboratory experiments, allowing learners to manipulate variables, observe outcomes, and repeat procedures safely. As a form of computer-assisted instruction, VLs integrate animations, simulations, and guided inquiry to enhance understanding of complex chemical processes (Adolphus & Omeodu, 2020). This paper therefore examines the issues limiting the integration of virtual laboratories in Nigerian secondary schools, explores their educational prospects, and proposes strategic measures for effective implementation.

Teaching Chemistry Practical in Secondary School

In chemistry, a practical refers to a hands-on activity or experiment conducted in a laboratory where students apply theoretical knowledge to observe chemical reactions, test hypotheses, and develop scientific skills. It usually involves performing experiments safely using chemicals and equipment, recording observations and measurements accurately and analyzing data to draw conclusions based on scientific principles. In short, a chemistry practical is learning chemistry by doing, rather than just reading or listening. Köller et al. (2015) defines practical work as "any type of science teaching and learning activity in which students, working either individually or in small groups are involved in manipulating and/or observing real objects and materials

Practical work is a defining feature of chemistry as a scientific discipline and constitutes a core component of secondary school chemistry curricula worldwide (Musengimana, et al. 2021; Smetana & Bell, 2012). Through laboratory activities, students acquire not only theoretical knowledge but also essential scientific skills such as observation, measurement, data interpretation, hypothesis testing, and safe handling of chemicals and equipment (Amba & Chinwendu, 2015; Adebayo & Olatoye, 2019). In the Nigerian context, chemistry practicals are a compulsory component of external examinations such as the Senior School Certificate Examination (SSCE) conducted by WAEC and NECO, underscoring their importance in both instruction and assessment (Aliyu & Talib, 2019; West African Examinations Council, 2023).

However, the effective implementation of chemistry practicals in many Nigerian secondary schools remains severely constrained. Most schools face shortages of basic laboratory equipment, reagents, and safety materials, while others operate without functional laboratories entirely (Emendu & Okoye, 2015). Overcrowded classrooms, poor maintenance culture, irregular electricity supply, and inadequate laboratory technicians further weaken practical instruction (Amba & Chinwendu, 2015; Lackaye & Zungu, 2020). Consequently, many teachers adopt teacher-centred approaches such as demonstrations or theoretical descriptions of experiments, which limit students' opportunities for hands-on engagement and meaningful inquiry (Aliyu & Talib, 2019).

These limitations have serious implications for students' learning outcomes. Practical chemistry is intended to bridge the gap between abstract concepts and real-world applications; when students are denied active participation in experiments, their understanding becomes superficial and rote-based (Musengimana et al., 2021; Smetana & Bell, 2012). This is reflected in persistent poor performance in chemistry practical examinations reported by WAEC and NECO, where students demonstrate weaknesses in experimental procedures, observation skills, and interpretation of results (National Examinations Council, 2017; West African Examinations Council, 2023). Therefore, while practical work remains indispensable to chemistry education, structural and resource-related challenges have made its effective delivery increasingly difficult in Nigerian secondary schools. This reality necessitates the exploration of alternative and complementary approaches, such as virtual laboratories, to enhance practical learning (Ali & Ullah, 2020; Su, 2019).

Virtual Laboratories as Instructional Media in Chemistry Education

Virtual laboratories (VLs) are structured digital learning environments that simulate real laboratory experiments using computer-based technologies. They are designed to replicate chemical processes, experimental procedures, and data collection in ways that support interactive, inquiry-oriented learning. When effectively integrated into instruction, virtual laboratories complement physical laboratory work by enhancing conceptual understanding, procedural skills, and learner engagement (De Jong et al., 2013). Virtual laboratories function as interactive instructional media that support communication, visualization, and learner engagement in science education. Unlike traditional instructional materials, VLs allow students to interact dynamically with simulated laboratory environments, observe microscopic processes, and explore cause-and-effect relationships that are often difficult to demonstrate physically. Victor-Ishikaku (2021) emphasizes that effective teaching requires the strategic use of instructional media to enhance clarity, interactivity, and learner comprehension. In this regard, virtual laboratories offer a powerful medium for communicating abstract chemistry concepts through visual and experiential representations.

As a subset of computer-assisted instruction, virtual laboratories combine multimedia elements such as animations, simulations, and digital models to replicate laboratory procedures. These environments enable learners to conduct experiments safely, repeat procedures multiple times, and learn at their own pace. Globally, VLs are increasingly used to complement physical laboratories by addressing limitations related to cost, safety, time, and accessibility (Ali & Ullah, 2020). However, despite their potential, the integration of virtual laboratories into Nigerian secondary school chemistry classrooms remains limited and uneven.

The successful integration of virtual laboratories into chemistry teaching requires deliberate pedagogical planning rather than mere technological adoption. Virtual laboratories should be aligned with curriculum objectives, lesson outcomes, and assessment practices to ensure that they meaningfully support student learning (Ali & Ullah, 2020; Makransky et al., 2020). As instructional media, virtual laboratories are most effective when used to complement, rather than replace, traditional laboratory activities (Su, 2019). One effective approach is blended laboratory instruction, where virtual laboratories are used before physical experiments as pre-lab activities. In this model, students explore experimental procedures, manipulate variables, and predict outcomes in a simulated environment prior to entering the physical laboratory. This preparatory exposure enhances students' familiarity with equipment and procedures, reduces errors during real experiments, and improves time management during laboratory sessions (Brinson, 2017; Makransky et al., 2020). After physical practicals, virtual laboratories can also be used for post-lab reinforcement, allowing students to repeat experiments, analyze results, and correct misconceptions (Tatli & Ayas, 2013; Su, 2019).

Virtual laboratories can also support inquiry-based and student-centred learning. Teachers can design activities in which students investigate chemical phenomena by formulating hypotheses, testing variables in the virtual environment, and drawing conclusions from simulated data. This promotes higher-order cognitive skills such as analysis, evaluation, and problem-solving, which are central to meaningful science learning (De Jong et al., 2013; Smetana & Bell, 2012).

Furthermore, virtual laboratories provide opportunities for inclusive and equitable instruction. In schools with limited laboratory facilities, large class sizes, or safety constraints, virtual laboratories ensure that all students have access to practical experiences. They are particularly useful for demonstrating experiments involving hazardous chemicals, expensive reagents, or complex apparatus that may not be available in many secondary schools (Ali & Ullah, 2020; Tatli & Ayas, 2013).

For effective integration, teacher competence and institutional support are critical. Teachers must be trained not only in the technical operation of virtual laboratory platforms but also in pedagogical strategies for embedding them into lesson plans, assessments, and classroom discourse (Koehler et al., 2014; Nnamonu et al., 2024). School administrators and policymakers must also provide supportive infrastructure, including reliable electricity, internet access, and appropriate digital devices to ensure sustainability and equitable access (Lackaye & Zungu, 2020). When thoughtfully implemented, virtual laboratories can transform chemistry teaching by expanding practical access, enhancing conceptual understanding, and fostering active learning. Their integration into secondary school chemistry instruction represents a pragmatic response to existing infrastructural limitations while maintaining the integrity of practical science education (Makransky et al., 2020; Su, 2019).

Core Components of Virtual Laboratories

Virtual laboratories are not merely digital replicas of physical laboratories; rather, they are complex instructional systems composed of interrelated technological and pedagogical elements. Understanding the components that constitute virtual laboratories is essential for evaluating their instructional effectiveness and for guiding their integration into chemistry teaching. These elements work together to create meaningful learning experiences that approximate, and enhance traditional laboratory activities. Virtual laboratories are composed of several interconnected components that together enable effective simulation, interaction, and learning in chemistry education. The major components include:

1. Simulation Engine

Simulation engines form the foundation of most virtual laboratories. These computational models represent chemical reactions, physical transformations, and experimental systems using algorithms that approximate real-world laboratory behavior. Through simulation, students can manipulate variables such as concentration, temperature, pressure, and volume and immediately observe resulting changes in reaction rate, equilibrium position, or product formation. This instant feedback enables learners to investigate cause–effect relationships that are often difficult to visualize or repeatedly test in conventional laboratories (Tatli & Ayas, 2013).

2. Multimedia and Visualization Interface

Multimedia interfaces enhance learning by integrating animations, diagrams, videos, and three-dimensional visualizations. Such representations are particularly valuable in chemistry, where many phenomena occur at the particulate or molecular level. Visualizing molecular motion, bond formation, and reaction mechanisms helps students connect macroscopic observations with microscopic explanations, thereby strengthening conceptual understanding (De Jong et al., 2013).

3. Interactive Tools and Virtual Apparatus

Interactive tools and controls allow learners to manipulate virtual laboratory apparatus such as burettes, pipettes, measuring cylinders, thermometers, and electronic balances. Students can follow step-by-step experimental procedures, repeat experiments, test alternative conditions, and correct mistakes without safety risks or material constraints. This promotes procedural knowledge and builds confidence before engagement in real laboratory activities (Tatli & Ayas, 2013).

4. Instructional Scaffolding and Guidance

Instructional scaffolds and assessment features are commonly embedded within virtual laboratory platforms. These include guided instructions, prompts, embedded quizzes, automated feedback, and data-logging tools that support formative assessment and self-regulated learning. Teachers can monitor learner progress, diagnose misconceptions, and adapt instruction based on performance analytics (Makransky et al., 2019).

5. Network, Accessibility, and Platform Support

Accessibility and network features allow virtual laboratories to be used online or offline across multiple devices, including computers, tablets, and smartphones. This flexibility supports distance education, blended learning, and individualized practice beyond the physical constraints of school laboratories, particularly in contexts with limited equipment or safety concerns (De Jong et al., 2013).

Types of Virtual Laboratories Used in Chemistry Teaching

Virtual laboratories in chemistry are not uniform; they vary in design, pedagogical intent, and level of realism. Common types include:

1. Simulation-Based Virtual Laboratories

These present simplified models of chemical systems that allow students to manipulate variables and observe outcomes in a controlled digital environment. They are widely used for topics such as reaction rates, chemical equilibrium, gas laws, and stoichiometry, where conceptual understanding of relationships between variables is essential (Tatli & Ayas, 2013).

2. Remote Laboratories

Remote labs enable students to control real laboratory equipment through the internet. Learners send commands to actual instruments and receive real-time data and visual feedback. Although not purely virtual, they provide authentic experimental experiences without requiring physical presence in the laboratory (De Jong et al., 2013).

3. Virtual Reality (VR) and Immersive Laboratories

These use three-dimensional, immersive environments—often through head-mounted displays or 3D interfaces—to simulate realistic laboratory settings. Students can "walk through" laboratories, handle virtual apparatus, and perform experiments in a highly interactive manner.

Research indicates that such environments can increase engagement and motivation when combined with appropriate instructional support (Makransky et al., 2019).

4. Game-Based and Inquiry-Oriented Virtual Labs

Some virtual laboratories are embedded within game-like or problem-based learning environments, where students investigate chemical scenarios, make decisions, and solve experimental challenges. These formats encourage inquiry, hypothesis testing, and higher-order thinking skills (De Jong et al., 2013).

5. Hybrid or Blended Virtual Labs

These combine digital simulations with physical laboratory activities. Students may first explore concepts in a virtual environment before conducting real experiments, thereby improving preparedness, reducing errors, and optimizing limited laboratory time (Tatli & Ayas, 2013).

Issues Limiting the Integration of Virtual Laboratories in Nigerian Secondary Schools

Inadequate ICT Infrastructure

One of the most significant barriers to the adoption of virtual laboratories in Nigerian secondary schools is inadequate ICT infrastructure. Many schools lack functional computer laboratories, sufficient hardware, reliable internet connectivity, and stable electricity supply. Ajayi (2017) observes that ICT facilities are particularly scarce in rural and under-resourced schools, making technology-based instruction difficult to implement. Recent reports indicate that fewer than 30% of public secondary schools in Nigeria have functional computer laboratories, while a substantial proportion of students lack basic digital skills (Lawal, 2025).

Limited Teacher Digital Competence

Effective integration of virtual laboratories depends largely on teachers' technological and pedagogical competence. Many chemistry teachers have limited training in educational technology and lack confidence in using digital tools for inquiry-based instruction. This skills gap often results in resistance to adopting new instructional approaches or superficial use of technology without pedagogical depth (Ajayi, 2017). Without sustained professional development, teachers may struggle to align virtual laboratory activities with learning objectives and classroom practices.

High Initial Costs and Sustainability Concerns

Although virtual laboratories can reduce long-term costs associated with consumables and equipment maintenance, the initial cost of acquiring software licenses, hardware, and internet services can be prohibitive for many schools. Budgetary constraints often limit schools' ability to invest in high-quality virtual laboratory platforms, particularly in public schools with limited funding (Lackaye & Zungu, 2020).

Curriculum and Policy Misalignment

The Nigerian secondary school chemistry curriculum does not explicitly mandate or guide the use of virtual laboratories, which limits their systematic adoption. In many cases, available VL platforms are not fully aligned with national curriculum objectives, making integration into lesson planning and assessment challenging. Although national policies acknowledge the importance of ICT in education, implementation and enforcement remain weak (Nnamonu et al., 2024).

Digital Inequality

Unequal access to digital devices and internet connectivity among students further constrains the effectiveness of virtual laboratories. Learners in urban and private schools often have greater exposure to digital resources, while those in rural or low-income communities face significant disadvantages. This digital divide risks exacerbating existing educational inequalities if not addressed through inclusive policy measures (Federal Republic of Nigeria [FRN], 2013).

Prospects of Virtual Laboratories in Chemistry Teaching

Enhanced Student Engagement and Motivation

Virtual laboratories align with students' familiarity and interest in digital technologies, offering interactive and visually rich learning environments. Simulated experiments, animations, and game-like features can increase learner motivation and sustain engagement. Hicks (2021) notes that immersive virtual learning environments encourage exploration and curiosity, helping students better understand abstract chemistry concepts such as molecular interactions and reaction mechanisms.

Safe and Cost-Effective Practical Experiences

Virtual laboratories provide risk-free environments for conducting experiments that may be hazardous or expensive in physical laboratories. By allowing students to observe procedures and practise techniques virtually, VLs can reduce accidents and improve preparedness for real laboratory work (Su, 2019). This approach is particularly valuable in schools with limited safety equipment or resources.

Flexibility and Accessibility

Unlike traditional laboratories that are constrained by time, space, and resource availability, virtual laboratories allow experiments to be conducted anytime and anywhere. This flexibility supports self-paced learning, repeated practice, and access for students who may have missed physical laboratory sessions. Mustafa and Deplau (2019) emphasize that virtual learning environments promote independent learning and mastery through repetition.

Expanded Access to Practical Learning

Virtual laboratories can serve large classes and remote learners, extending practical exposure beyond the capacity of physical laboratories. Free or low-cost platforms such as PhET and ChemCollective provide opportunities for continuous practice and reinforcement of classroom learning (Aliyu & Talib, 2019).

Conclusion

This paper examined the challenges and prospects of integrating virtual laboratories into chemistry teaching in Nigerian secondary schools. Persistent underachievement in chemistry, particularly in the practical component, is linked to inadequate laboratory facilities, limited instructional time, safety concerns, and insufficient teacher capacity. The paper argues that, when used as complementary instructional media, virtual laboratories provide a pragmatic and scalable response to these challenges by enhancing conceptual understanding, student engagement, and access to practical experiences. However, their effectiveness depends on appropriate pedagogical integration, teacher competence, infrastructural support, and curriculum alignment. Overall, virtual laboratories should not replace physical laboratories but serve as strategic innovations capable of bridging existing gaps and improving the quality, equity, and effectiveness of chemistry education in Nigeria. To ensure the effective and sustainable integration of virtual laboratories in secondary school chemistry education, it is therefore suggested that government and school authorities should prioritize investment in ICT infrastructure and subsidize access to appropriate virtual laboratory platforms. In addition, continuous professional development programmes should be institutionalized to strengthen teachers' competence in digital pedagogy and the pedagogical use of virtual laboratories. Curriculum developers and examination bodies should explicitly embed virtual laboratory activities within the chemistry syllabus and assessment frameworks to promote systematic adoption. Strategic partnerships among government agencies, non-governmental organizations, and technology providers should also be strengthened to expand access to high-quality, curriculum-aligned virtual laboratory resources. Finally, a national monitoring and evaluation framework should be established to assess implementation effectiveness, guide continuous improvement, and ensure long-term sustainability.

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