



Teacher Readiness, Student Participation and Sustainable Utilisation of Blended Physical–Virtual Chemistry Laboratories in South-East Nigeria

Nwokorie O. Smart

Department of Science Education, Faculty of Education, Abia State University, Uturu, Nigeria

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ABSTRACT

This study investigates how three variants of lesson configuration: physical laboratory, virtual laboratory and integrated (blended) laboratory, influence teaching readiness and student participation in the sustainable utilisation of chemistry laboratories. The study was restricted to South-east Nigeria and evaluated 30 public secondary schools and 90 chemistry teachers and 600 senior secondary school students. Based on the primary research findings, the acceptance level of teaching readiness among the chemistry teachers investigated was high, in all the three laboratory variants. Student participation was found to be generally low, with inclination towards cognitive and collaborative participation. The findings suggest that the acceptance of sustainable utilisation of laboratory was generally positive and influenced by several factors including the practicality and support of the teachers and the administration. One way ANOVA revealed a significant difference, at $p < 0.001$, in the mean scores of teacher readiness, student participation and sustainable utilisation in all the three laboratory variants. The blended condition outperformed the others in terms of the mean scores on readiness ($M = 85.63$), participation ($M = 86.53$), and sustainable utilisation ($M = 83.55$). Furthermore, all pairwise comparisons among the conditions were significant at $p < .001$. In the cluster-robust model, teacher readiness and school-level student participation were predictors of sustainable utilisation and were significant (teacher readiness: $B = .340$, $p < .001$; school-level student participation: $B = .554$, $p = .002$), and the remaining mechanisms of action (modality) lost significance. The results showed that, of the three available conditions, blended conditions showed the best results. Considering the results, the main reason for blended conditions showing better results is teacher capacity and student participation. The study developed and proved that integration of Chemistry laboratory services in South-East Nigeria is feasible through different, yet complementary, methods and approaches, especially if teacher training and capacity development is incorporated, along with the use of digital and other offline resources, functional school laboratories and continuous and regular school-level inspection.

Keywords: Chemistry education; teacher readiness; student participation; sustainable utilisation; physical laboratory; virtual laboratory; blended laboratory; South-East Nigeria.

INTRODUCTION

Laboratory education is distinctive in education and training of the sciences, because learning occurs by integrating symbolic representations of a discipline with its material or physical forms. Chemistry laboratory education is a good example of this. Students learn how to dissolve and/or combine substances, gauge and manipulate laboratory apparatus, and take control of laboratory processes to make conclusions based on observations (e.g., explain and analyse phenomena, measure and/or interpret data, draw conclusions, justify/evaluate). The traditional view and emphasis in laboratory education has been on the safety of students and the utilisation of laboratory facilities. New trends have been directed toward integration of virtual laboratories and conceptualising different ways and means of laboratory work and/or activity, all in the service of supporting students' understanding and integration of theoretical and practical aspects of a subject or field of study. Contemporary research and reviews offer a compelling argument and confirm benefits accruing from the virtual laboratory work in the domain of chemistry education.



There are other reasons to study the integration of virtual and physical laboratories apart from the challenges related to COVID-19. The Federal Ministry of Education has released several policies that address challenges with digital education. The National Digital Learning Policy and the National EdTech Strategy address a range of challenges, and demonstrate the importance of effective digital teacher training and delivery of digital education, and address challenges with Digital Education infrastructure. Of the policies released by the Federal Ministry of Education, Chemistry Education has the greatest challenges with integration due to the complexity of digital practices. Many schools, particularly in urban areas, are equipped with ICT infrastructure and laboratory equipment, however, for a variety of reasons, these facilities are frequently underutilized. Conversely, a large number of schools, particularly in rural and disadvantaged areas, are lacking basic education and laboratory facilities. Therefore, for Education to be provided sustainably, it is crucial that a range of digital and non-digital equipment and learning resources be made available to teachers and learners, rather than building or repairing new or existing infrastructure.

Knowledge about education practices in Nigeria is increasing; however, it is uneven. In Enugu State, for example, Onyinye, Egbo and Agujiobi (2023) found that learning Chemistry through a virtual laboratory increased student performance compared to the performance of students in a demonstration control group. In Anambra State, Ezeudji (2025) found that the use of ChemLab software positively impacted student performance and class participation as well as the development of practical skills; and that the use of a virtual laboratory positively impacted student Chemistry performance compared to the use of a traditional (wet) laboratory. Similar positive impacts of the use of virtual laboratories have been documented for other states of the country, and for other subjects. For example, in Delta State, virtual laboratories improved the performance of students in Chemistry (Avwiri and Odiri, 2025); improved retention of students in a virtual course (Jack and Shidawa, 2025), and improved the performance and retention of students in Cross River State (Anari et al., 2026). An offline virtual laboratory improved acid/base titration practical skills in Bayelsa State (Konyefa, 2026).

However, these results should not be misinterpreted to suggest that virtual laboratories can fully replace real-life laboratories. Evidence from the international field suggests that virtually preparing students for real laboratories is appreciated, but substituting lab work with virtual lab work is not accepted. Virtual-reality based training for laboratory work has its positives, but is not without its limitations. Examples from virtual Chemistry laboratories suggest similar findings to what is obtained from traditional, lab-based Chemistry, and positively impact performance in a virtual setting, if the individual has background knowledge in Chemistry. Compared to traditional laboratory work, virtual lab work does have benefits, and moderately positively impacting students' performance in Chemistry, but this positively impacting performance depends on the knowledge background of the individual. The work done by Ariyo and Sunday (2025) is of particular importance to this research, as the blended learning condition positively impacted students' performance and confidence. The findings discussed above reshape how the policy interval is framed, allowing for the integration of both virtual and real laboratories in education.

A major shortcoming in existing studies is that they tend to ignore the conditions that facilitate the continuation of an intervention. Many of the reported interventions yielded positive short-term effects on student achievement, but the benefits often disappeared after the intensive support and/or the researchers and tools withdrawn from the situation. For the successful and sustained implementation of an intervention, teachers must be able to integrate the required technologies in teaching and learning to cope with situations for which they are not adequately prepared. They must further be able to control potential dangers posed by the use of the technologies in school laboratories and integrate the technology in ways to aid the achievement of curriculum goals and objectives and facilitate achievement of instructional goals and objectives. It has been reported in the Nigerian context that the digital readiness of teachers is inadequate. Further reports indicated that Chemistry teachers in secondary schools owned by the government of Anambra State lack adequate and appropriate digital learning contents and that the teachers, generally, lack knowledge of ICT. Another report suggested that, with respect to integration of digital technology in various curriculum areas, the teacher had a positive attitude and perceptions, low level of competence and control, and that there were numerous and challenges constraints.



Considering the above, the present study takes a different approach and focuses on three implementation aspects, namely; teacher readiness, student participation, and sustainable use of labs. Teacher readiness implies the competency level of a teacher to plan and conduct a laboratory session. Student participation involves the behavioural, cognitive and social aspects of students while learning in a laboratory. Sustainable use of laboratories implies the institutional commitment to use a laboratory approach in learning over a long period. These components are examined in physical, online and integrated physical and online (blended) formats of teaching in public secondary schools in Abia, Anambra, Ebonyi, Enugu and Imo States.

The aim of using the three group comparison is to assess whether there exist statistically meaningful average differences, to quantify these differences, to identify from which aspects of comparison these differences were made, and to determine whether there exist any modalities (E.g. teacher readiness, student participation and available infrastructure) which give an advantage to any of the formats of instruction. This last aspect is of main interest.

In the presence of other variables, e.g. teacher readiness and student participation, if the blended condition records the highest level of sustainable utilisation but the modality coefficient becomes insignificant, it may be justifiable to conclude that the evidence is an outcome of the context rather than the blending of instructional delivery. Of special interest in such cases is to identify the context within which the evidence is observed, since the context and other associated variables may be altered to affect positive change.

The study is intended to provide answers to the following research questions; (1) do teacher readiness levels differ for the various physical, virtual and blended approaches to laboratory work? (2) do student participation levels vary for the different approaches to laboratory work? (3) does sustainable utilisation vary for the different approaches? and (4) what do implementation conditions, if any, alter sustainable utilisation? The answers to the research questions are based primarily on field data collected from teaching staff and Senior Secondary School students in the sampled schools in South-East Nigeria.

LITERATURE REVIEW

Educational Functions of Physical, Virtual and Blended Chemistry Laboratories

The nature of the practical constraints of chemistry lends itself to study in the physical laboratory. In the physical laboratory, equipment may malfunction, menisci may not be read correctly, endpoints of a reaction may be missed, and reagents may be spoiled. Learning to negotiate the constraints of equipment, reagents, and procedures, and adapting to the unanticipated consequences of reactions is an important, yet difficult, aspect of a chemistry education. Learning to execute practical procedures and demonstrating psychomotor skills to evaluate the progress of a reaction and/or assess its outcome are important aspects of a chemistry education. The physical laboratory provides the setting for learning to adapt and respond to the unanticipated outcomes of practical chemical reactions and learn the procedural skills and psychomotor skills to accomplish practical procedures. The equipment of the physical laboratory can provide the setting to support students to learn different practical procedure roles. Each of these advantages have costs. The equipment must be well maintained and the laboratory prepared to ensure sufficient materials are available for the class. In schools with limited resources, the ability to conduct laboratory courses is largely dependent on the commitment and preparation of the teacher to ensure sustained use of the laboratory equipment.

Virtual laboratories offer a range of benefits for users, from demonstrating molecular processes to reducing exposure to hazardous substances. In Tatenov et al. (2023), the use of an interactive virtual lab in inorganic chemistry improved user's ability to reason and process skills as well as learning outcomes. Preparatory use of virtual labs to teach and demonstrate processes and concepts in science has been shown to be effective in improving the teaching of pre-service science teachers. A series of systematic reviews published in 2024 and 2025 support the use of virtual labs for improving science process skills, and the abilities of learners to engage critically in and with science, while highlighting the limits of using virtual labs for the development of manual skills in science, and the potential inequities that may exist (Rosli and Ishak, 2024; Deriba, Saqr and Tukiainen, 2024; Meronda, Widarti and Yahmin, 2025).



Physical- and virtual-laboratory environments, which are generally treated as mutually exclusive, can be integrated to enhance students' learning. Initially, students can use the virtual environment to become familiar with the experimental apparatus, simulate the required experimental procedures, and test their hypotheses, if any. Students can perform the actual experimental procedure in the next class by focusing on the real experiment, that is, setting up the apparatus, performing the procedure, and obtaining results. Students can use the post-lab virtual environment to explain the results of their laboratory experiment. Connecting the dots, Mojsoska et al. (2024) and Viitaharju et al. (2023) noted that preparing students with virtual training enhances their understanding of laboratory experimentation and increases the efficiency of time devoted for performing laboratory experiments. Taking into account the Nigeria-specific evidence reported by Ariyo and Sunday (2025), this concept is likely to be of great benefit in Nigeria, as well. Chuang, Abdul Rabu and Jamiat (2026) extended the findings of Mojsoska et al. (2024) to the virtual environment and reported positive effects on students' achievements in laboratory.

Teacher Readiness as an Implementation Condition

The nature of teacher readiness is multidimensional. An exemplary college Chemistry teacher may have expert subject matter knowledge but have limited ability using or troubleshooting online learning platforms. Another teacher may be an expert at utilizing various learning platform features but have insufficient knowledge about Chemistry or pedagogy to determine if and when a simulation should be used in lieu of a traditional chemistry laboratory. Yet another teacher may have the ability to incorporate both traditional and digital learning, but have insufficient confidence in dealing with the safety and logistical concerns of a large classroom. Thus, the nature of teacher readiness is more appropriately conceptualised as integration of multiple dimensions of teacher readiness and should not be reduced to teacher's computer literacy.

The multidimensional nature of teacher readiness has recently been documented in research within the Nigerian context. For example, Igboanugo (2024) found that during the integration of digital technology in Chemistry teaching, gender did not differ in the readiness of 410 in-service secondary school Chemistry teachers. Na'Allah (2026), in a different study in Anambra State, noted the presence of a positive attitude among Chemistry teachers towards the use of information communication technology (ICT), but found that several constraining factors such as insufficient training and limited ICT infrastructure adversely impacted teachers' digital competence. A clue to the nature of the multidimensional readiness to integrate digital technology among Chemistry teachers in Nigeria may be found in studies documenting the presence of positive attitudes among teachers toward new technological developments and innovations.

Similar tendencies are observed outside Nigeria. Based on the technology acceptance model, Shambare and Jita (2024) indicate that most science teachers in rural areas of South Africa have a positive view towards virtual laboratories and are willing to adopt them, but have low competencies to use them. Likewise, Shambare and Jita (2025) affirm that creating an enabling condition and providing support for implementation may enhance teachers' intent to use virtual laboratories. These conditions and support structures are vital to ensure that intent to use virtual laboratories is realised. Like in South East Nigeria, schools have variations in the consistency of electricity, the availability of teaching and learning resources including science equipment and kits, and the presence of ICT and science support facilities. Where such support is lacking, teacher intent may not be sustained. Therefore, it is important to align the support conditions for the intent to use virtual laboratories.

Management of virtual and physical laboratories places different demands on teachers' competence, skills, and knowledge in using various equipment and materials. Management of a virtual laboratory, for example, requires competence in using the ICT equipment and digital resources to prepare and upload educational content for online teaching and/or for participants to engage in self-directed, independent learning. Blended learning, thus, requires integration of virtual and physical aspects of teaching and supportive integration of competences from different modes. Teachers are, however, deemed to become competent to manage different aspects and modes of integrated instruction.



Student Participation and the Quality of Laboratory Experience

There are multiple forms of participation. Some are physical and behavioural, while others are intellectual and social. Physical and behavioural forms include attendance, bodily movement, motion, manipulating supplies and material, and effort. Intellectual participation includes planning, predicting, and explaining. Socially participation includes discussion and negotiation. Each of these elements of participation varies among the several types of laboratory activities and among the several types of laboratory equipment. During a practical in which students prepare and carry out a chemical synthesis, some may control the equipment, while the rest of the class may observe. On the other hand, a virtual laboratory may provide students with opportunities to individually manipulate variables. It becomes pedagogically harmful if the laboratory activities require the students to perform a series of mouse-clicks in the appropriate sequence to complete the laboratory.

Differentiated participation has been emphasised in recent chemical education. Ezeuduji (2025) reported a series of focus groups in which the use of ChemLab software in Anambra State, Nigeria, was discussed. Many participants reported improvements in their understanding of some chemistry concepts. Other participants reported positive attitudes toward virtual chemistry simulations. Participants of a focus group on motivation reported no changes in their motivation toward using virtual chemistry laboratories. In a series of focus groups in Serbia, the use of a virtual reality programme was reported to result in increased cognitive participation and a more active role of students toward a chemistry practical (Mojsoska et al, 2024). These research findings confirm that the main limitation for increased participation is the creativity and quality of design of an instructional programme, rather than the technology used.

Physical labs pose participation barriers as well. In some classes, only a few students have the opportunity to manually interact with lab equipment while the rest either watch or repeatedly document the results. Demonstrations and simulations may take the place of student lab manipulations due to equipment shortages. Student safety may constrain the type of activities students can do. Virtual activities may help increase student opportunities to interact with equipment and perform activities at their own pace. Virtual activities can also be done offline. Access to offline virtual activities is still limited, but more research has shown positive results for this activity type. For in-person activities, the most defensible participation model is one that integrates physical and virtual activities to achieve the desired learning outcome.

Sustainable Utilisation of Laboratory Innovation

“Sustainability” in educational technology is often synonymous with “purchasing.” True sustainability is continuous use of an innovation in the teaching and learning process. Of prime consideration in determining the sustainability of an instructional innovation is the extent to which it can be utilised repeatedly by educators to teach in varied instructional situations within the regular school environment with the normal resources available; if it can be easily and regularly employed without extensive and/or special support by an external agent; if it can be employed and used on an ongoing basis at a minimal cost; if it is easily accessed by learners; and if it can be employed to teach what is required to be learned. Zhang and Liu (2024) opine that virtual laboratories are sustainability-friendly innovations since they provide flexible access to laboratory situations, reduce the risks and costs of materials consumption, and facilitate the saving of non-renewable resources. On the other hand, Deriba, Saqr, and Tukiainen (2024) have shown that, for various reasons (e.g. cultural and lingual contexts) virtual and blended laboratories still have inequitable access.

It is prudent for countries to link integrally digital, social and financial capital, the same way Nigeria’s latest education policy and strategy has done (Federal Ministry of Education, 2023; Federal Ministry of Education, 2025). For Chemistry, especially, a digital blended approach is desirable. There is a symbiotic relation between a physical and digital laboratory. Sustaining a chemical-based laboratory calls for the right blending of both a physical and digital layer.

It is behavioural and organisational at its core. Teachers require preparation time to integrate two linked learning environments. School leaders need to protect teachers’ practical periods. Continuity requires that equipment, software, and staff be available. Innovations that depend on the efforts of a single teacher may

cease with that teacher's reassignment or transfer. Similar to teaching, student participation decreases when virtual activities do not seem to be related to the learning outcome, or if they are substitutes for practical work. Therefore, sustainable use of ICTs in science teaching is considered, in this study, a behavioural and organisational science capacity, or rather, a behavioural and organisational combination of personnel, infrastructure and structure of the laboratory rather than the simple collection of instruments and equipment.

Evidence from Nigeria and South-East Nigeria

South East Nigeria is particularly relevant since recent studies have shown that virtual laboratories provide evidence of teachers training in the use of educational technology in science teaching. Onyinye, Egbo and Agujiobi (2023) stated that the use of virtual Chemistry laboratories improved achievement in students in Enugu state. In Anambra state, ChemLab, an ICT-based educational resource, improved students' achievement, class participation and practical skills (Ezeuduji, 2025). In another study, the use of virtual Chemistry laboratories improved students' achievement in Ogidi education zone of Anambra state (Akachukwu and Nwankwo, 2026). Teacher-centred studies in Anambra state noted low or irregular trainings of teachers on the use of ICTs (Igboanugo, Odimekpa, and Dike, 2026; Igboegwu, 2026). The aforementioned studies provide evidence on how educational outcomes can be improved in the absence of systems to ensure sustainability of use.

This region is also internally differentiated. The states of Abia, Anambra, Ebonyi, Enugu and Imo house urban, peri-urban and rural areas. These differ by reliability of electricity and telecommunications, level of school funding and access to laboratory facilities. At the Alex Ekwueme Federal University Ndufu-Alike, Igboanugo (2024) studied the level of preparedness of teachers in digital skills. Other teacher digital preparedness studies have been conducted at the federal science and technical colleges that are also situated in Abia, Anambra and Ebonyi. These study locations demonstrate that regional coverage of science and technology infrastructure and facilities is inadequate. South-East Nigeria must also not be treated as a region that is homogeneous for IT and other related infrastructure.

Evidence from elsewhere in Nigeria remains valuable for establishing contextual standards. An aromatic nitro-reduction study conducted under blended and virtual modes of learning by Ariyo and Sunday (2025) demonstrated blended learning to be the most preferred, effective and safe mode among learners in Ondo State. Other studies in Delta state (Avwiri & Odiri, 2025), Cross River state (Jack & Shidawa, 2025) and Bayelsa State (Anari et al., 2025) have also reported positive findings. The studies further point to the necessity for additional research to address shortcomings in learning of science practical skills. Because varying results have been recorded, the current study explores the range of differences and what affects implementation the most.

Theoretical and Analytical Framework

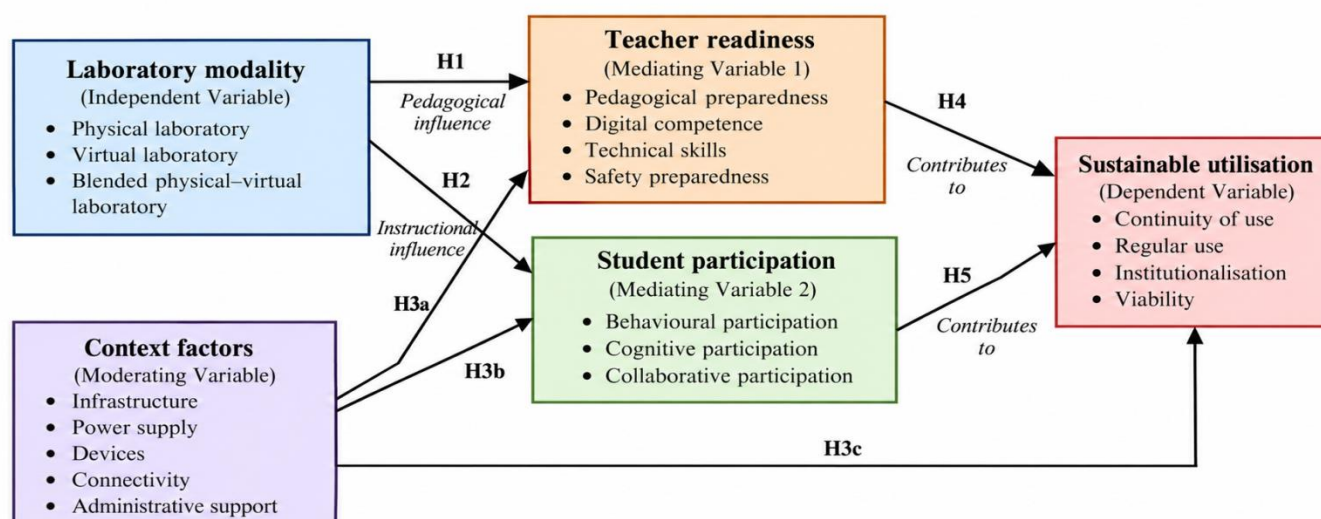


Figure 1. Conceptual framework linking modality, readiness, participation and sustainable utilisation.



The participation to sustainability logic contains some elements of the teacher's readiness to teach chemistry and integrates the knowledge and skills of modern ICT to perform chemistry virtual and other laboratory work. Shambare and Jita (2024) represent teacher's readiness to teach in TPACK theory as knowledge, pedagogy and technology integration towards the attainment of a virtual chemistry laboratory work in which other teachers' readiness is complemented by acceptance and implementation of the idea, as represented in teacher's readiness to perform chemistry virtual and laboratory work. Student participation is described in the chemistry classroom as the creation, guidance and stimulation of classroom activities related to students' explanations and participation. A teacher who is sufficiently prepared, based on the understanding of student participation, is able to organise various activities to promote student participation and stimulate classroom interaction within the lab.

Sustainable utilisation is a distal implementation outcome. The authors argue that factors such as cost and ease of instruction in a lab setting may result in sustainability differences between the three modalities (face-to-face, online, and blended). Blended learning may be more sustainable in that online learning may allow students to practice lab activities with less use of lab materials, thus making more lab materials available for other students to use in face-to-face activities. However, if other factors such as teacher readiness and student participation are controlled, then it would be correct to interpret that the blended approach requires teacher integration of the modalities and participation of students in a way that warrants the additional effort by the teacher. Consideration of the different approaches to lab settings and associated differences in equipment and technology is warranted.

Research Hypotheses

Four null hypotheses focus the research. These are: H0₁: with respect to the three modalities (face-to-face, online, and blended), there are no differences in teacher readiness to implement the various laboratory approaches; H0₂: the same is true for student participation; H0₃: the same is true for sustainable utilisation; and H0₄: the same is true when other contextual variables (i.e. teacher readiness, student participation, and laboratory modality, and infrastructure) are considered.

METHOD

Research Design

The study utilised a comparative research design that was both cross-sectional and multilevel. The design encompassed three conditions: physical-only, virtual-only, and blended physical and virtual conditions. The authors noted that the design allowed them to study variations in implementation conditions and associated outcomes. The variation studied does not imply the design assigned the conditions to the participants and the designers of the study do not mean to claim or suggest the variations studied establish any cause and effect relationship. Schools were viewed as analytical units to account for the fact teachers and students working in the same school may be exposed to similar implementation conditions. Field data were collected from teachers and students.

Study Setting and Sampling Structure

The study was conducted in five states that comprise the South Eastern region of Nigeria, including Abia, Anambra, Ebonyi, Enugu and Imo. A final field representation of the sample comprised 30 public, secondary schools, that is, six schools were represented from each of the five states. Researchers designated 10 schools to each condition and 30 teachers to each condition from the sample. Researchers aimed to have a balance in the representations and a fair sampling structure.

The term "physical only" describes an instructional situation when teaching a practical Chemistry skill in which a digital simulation is not incorporated. The term "virtual only" refers to use of a digital simulation in teaching the practical skill. A combination of the two methods (i.e. a blended approach) refers to a situation when a digital simulation is purposely incorporated to aid the teaching of a practical skill. Blended ICT



provision describes the use of a digital learning activity purposely to support the teaching of a practical Chemistry skill in which the teacher integrates and sequences the use of both ICT and non-ICT activities.

Variables and Measurement

A composite variable encompassing digital, pedagogical and technical competencies is utilised to assess a teacher's readiness to embrace the integration of ICT within the chemistry laboratory. Further components include safety, recent professional development, as well as school context. Each element is assessed using a Likert scale of 5 points. Logic and rationale underlying the construct of the variable is based on empirical evidences from Nigeria (2024-2026) which assert that the readiness of a teacher to integrate ICT within the educational setting, teacher's attitude, and the teacher's ICT skills are conceptually related yet measurably distinct variables. It is assumed that the teacher, based on training, will have the competence to routinely integrate ICT within the chemistry laboratory in a safe and pedagogically sound manner.

Student participation is measured on a 0-100 scale and reflects behavioural, cognitive and collaborative participation. Participation is defined behaviourally by degree of task completion and persistence, and may also be cognitively defined by level of prediction, interpretation and/or explanation. Participation may also be defined collaboratively by degree of role sharing and peer discussion and/or joint problem solving. Student participation is not defined by access to technology or reliability of the Internet. Participation is measured on a 0-100 scale and reflects individual's level of confidence in employing technologies. Conceptual understanding is also measured on a 0-100 scale. It is possible for an individual to participate in an online activity and to handle a piece of equipment in a laboratory, but to have little understanding of how to use the equipment.

Table 3. Operationalisation of principal and supplementary constructs

Construct	Operational indicators	Scale / role
Teacher readiness	Digital competence; pedagogical integration; technical readiness; safety readiness; recent training	0–100 principal outcome
Student participation	Behavioural involvement; cognitive engagement; collaborative participation	0–100 principal outcome
Sustainable utilisation	Continuity; regularity; school support; feasibility; resource viability	0–100 principal outcome
Practical confidence	Confidence in authentic apparatus handling and practical procedure	0–100 supplementary outcome
Conceptual engagement	Engagement with explanation, molecular representation and interpretation	0–100 supplementary outcome

Note. Composite indices were expressed on 0–100 scales; higher scores indicate higher levels of the respective constructs.

Data Collection and Management

To study constructs, research instruments (instruments in research) were constructed for teachers and students. For teachers, the constructs included integration of digital pedagogy and the sustainable use of school infrastructure; recent training and frequency of use of school digital labs; and, teacher readiness. For students, the constructs included behavioural involvement and collaboration; and cognitive engagement, and practice as well as conceptual engagement.

Data was collected in a way that permitted analysis of teachers' and students' responses in the context of school policies regarding online or integrated (blended) teaching and learning.

After collection, teachers' and students' responses were organised according to non-identifying school codes (S01 to S30). The organisation allowed for analysis of teachers' and students' responses without identifying information. Only statistics were generated from the data sets and the information was reported in the article. The workbooks contain teachers' and students' response data and statistical information reported in this article.

Statistical Analysis

Separate analyses of descriptive statistics were performed for each experimental condition. Hypothesis testing for H01-H03 and associated outcomes was performed using one-way analysis of variance (ANOVA). Levene's test was performed to evaluate the assumption of equal variance. As the Levene tests for each of the reported outcomes were not statistically significant, the analysis was performed using routine ANOVA. The effects of the laboratory condition were assessed using eta-squared (η^2). For comparison, the magnitude of effects are provided for small ($\eta^2 = .01$), medium ($\eta^2 = .06$), and large ($\eta^2 = .14$) effects. When the overall ANOVA was statistically significant, the family of related comparisons was defined using Tukey's honestly significant difference procedure.

Regarding sustainable use, a cluster-robust ordinary least squares regression model was performed to analyse the role of teachers. The model included the following conditional influences: teacher readiness and teacher practice, school mean student participation and classroom instructional materials, adequacy of school and classroom infrastructure and digital equipment, and laboratory condition. Adequate control was provided for extraneous variables using the cross-classification approach. The Regression model was assessed for overall and individual component significance using an alpha (α) level of .05. Routine probabilistic (p) values were reported. In cases where $p < .001$, a very small probability was assumed. The model is not assessed for causal mediation, due to the lack of temporal sequence in the cross-sectional data. Rather, the model evaluates whether there is a difference in laboratory mode of instruction after considering influencing factors.

Validity of the Analytical Interpretation

The interpretation of the results is strengthened in three ways. First, teacher- and student-level constructs were treated at their respective levels. Student participation was aggregated at the school-level when predicting sustainable use by teachers. Second, use of cluster-robust standard errors allowed researchers to treat teachers within the same school as a single, depressed observation. Lastly, practical confidence and conceptual engagement were studied to address other outcomes of the main study. Given the cross-sectional nature of the data and the sampled schools, interpretation is limited to the context of the study. Future studies are expected to address the gaps in the existing body of knowledge through long-term studies and studies in schools in various locations that are differently owned and resourced.

RESULTS

Descriptive Pattern Across the Three Laboratory Approaches

The physical, virtual, and blended groups are consistent in their use of the technologies and strategies provided, thus demonstrating an implementation gradient. Mean teacher readiness was 67.70 (sd = 5.16) in the physical group, 78.60 (sd = 6.90) in the virtual group, and 85.63 (sd = 5.04) in the blended group. Students also demonstrated the same ordering. The mean scores were 69.34 (sd = 7.14) in the physical group, 73.98 (sd = 7.34) in the virtual group, and 86.53 (sd = 7.57) in the blended group. In terms of sustainable utilisation, the physical, virtual and blended groups showed mean scores of 63.33 (sd = 5.45), 70.38 (sd = 4.55) and 83.55 (sd = 4.70), respectively. Thus, in comparison to the physical group, the blended group was 17.93 points higher in mean teacher readiness, 17.19 points higher in mean student participation, and 20.22 points higher in mean sustainable utilisation.

The supplemental educational outcomes provide a qualified exception to this trend. Confidence was highest in the blended condition (M = 85.62, SD = 6.75), followed by the physical condition (M = 79.04, SD = 7.04), and the virtual condition was the lowest (M = 67.25, SD = 6.79). Reversed ordering was evident with respect to conceptual engagement. The physical condition was the highest (M = 71.14, SD = 5.92), followed by the virtual condition (M = 78.13, SD = 6.04), and the blended condition was the lowest (M = 86.14, SD = 6.07). In the case of the development of confidence with physical equipment, a virtual environment was of least help. A blend of the environments was of the most help.

Table 4. Descriptive statistics by laboratory approach

Outcome	Physical M (SD)	Virtual M (SD)	Blended M (SD)
Teacher readiness	67.70 (5.16)	78.60 (6.90)	85.63 (5.04)
Student participation	69.34 (7.14)	73.98 (7.34)	86.53 (7.57)
Sustainable utilisation	63.33 (5.45)	70.38 (4.55)	83.55 (4.70)
Practical confidence	79.04 (7.04)	67.25 (6.79)	85.62 (6.75)
Conceptual engagement	71.14 (5.92)	78.13 (6.04)	86.14 (6.07)

Note. Statistics are based on the primary field dataset collected from the sampled schools.

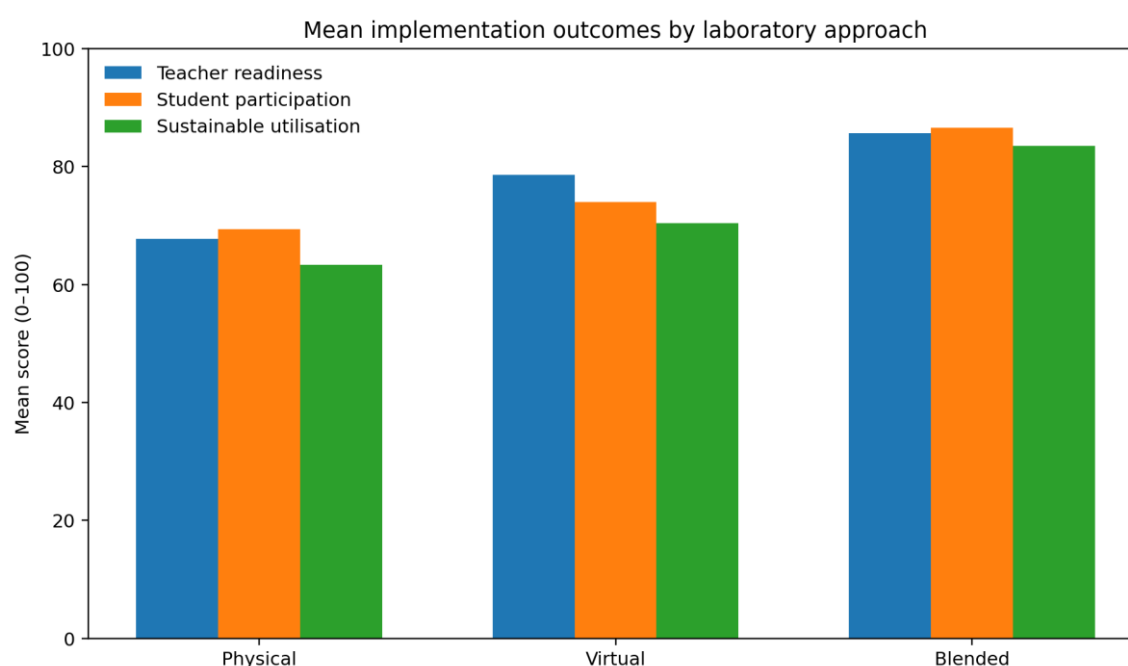


Figure 2. Mean teacher readiness, student participation and sustainable utilisation by laboratory approach.

Omnibus Tests of Group Differences

The first null hypothesis stated that there was no difference in teacher readiness across laboratory conditions. The results of the analysis indicated that teacher readiness differed across laboratory conditions, $F(2, 87) = 73.676$, $p < .001$, $\eta^2 = .629$. The effect size indicated that 62.9% of the variance of the sample was due to the difference in teacher readiness across laboratory conditions. Levene's test of equality of error variance was non-significant, $F(1, 43) = .871$, $p = .422$, and therefore, it was assumed that the variance of the population across the groups was equal. The second null hypothesis indicated that there was no difference in student participation across laboratory conditions. The results of the analysis indicated that student participation differed across conditions, $F(2, 597) = 292.738$, $p < .001$, $\eta^2 = .495$, with a non-significant Levene test, $F(1, 43) = .845$, $p = .430$. It was also hypothesised that there was no difference in the sustainable use of technology across laboratory conditions. The results of the analysis, however, indicated that there was a difference across conditions, $F(2, 87) = 130.793$, $p < .001$, $\eta^2 = .750$, with Levene test of equality of error variances, $F(1, 43) = .469$, $p = .627$. By the criteria of eta-squared, all effects of modality were large.

The results of the hypothesised differences in the remaining variables were also in the expected direction. Differences in the means of the samples were interpreted as practical confidence, and these differed across conditions, $F(2, 597) = 367.754$, $p < .001$, $\eta^2 = .552$. Differences in the means of the samples as conceptual engagement also differed across conditions, $F(2, 597) = 311.795$, $p < .001$, $\eta^2 = .511$.

Table 5. One-way ANOVA and effect-size results

Outcome	F	p	η^2	Levene p	Decision
Teacher readiness	73.676	<.001	0.629	0.422	Reject H01
Student participation	292.738	<.001	0.495	0.43	Reject H02
Sustainable utilisation	130.793	<.001	0.75	0.627	Reject H03
Practical confidence	367.754	<.001	0.552	0.558	Significant
Conceptual engagement	311.795	<.001	0.511	0.716	Significant

Note. Statistics are based on the primary field dataset collected from the sampled schools.

Post-hoc Pairwise Comparisons

According to Tukey post-hoc comparisons, all three main outcomes of the study were statistically significant in all pairwise comparisons. In the case of teacher readiness, it was found that the blended condition was superior to both the physical and virtual conditions by 17.92 and 7.03 points, respectively, and the virtual condition was also superior to the physical condition by 10.90 points. It was also found that the blended condition of student participation was superior to both the physical and virtual conditions by 17.19 and 12.55 points, respectively, and the virtual condition of student participation was superior to the physical condition by 4.64 points. Finally, it was found that the blended condition of sustainable utilisation was superior to both the physical and virtual conditions by 20.23 and 13.17 points, respectively, and the virtual condition of sustainable utilisation was superior to the physical condition by 7.06 points. The findings, therefore, indicate that the three conditions of laboratory in the case study schools exhibit three different profiles in the case study field situation.

Table 6. Tukey post-hoc comparisons for the principal outcomes

Outcome	Comparison	Absolute mean difference	Adjusted p
Teacher readiness	Blended vs Physical	17.92	<.001
Teacher readiness	Blended vs Virtual	7.03	<.001
Teacher readiness	Virtual vs Physical	10.9	<.001
Student participation	Blended vs Physical	17.19	<.001
Student participation	Blended vs Virtual	12.55	<.001
Student participation	Virtual vs Physical	4.64	<.001
Sustainable utilisation	Blended vs Physical	20.23	<.001
Sustainable utilisation	Blended vs Virtual	13.17	<.001
Sustainable utilisation	Virtual vs Physical	7.06	<.001

Note. Statistics are based on the primary field dataset collected from the sampled schools.

Predictors of Sustainable Utilisation

The cluster-robust regression model accounted for 81.5 percent of the variance for sustainable utilisation ($R^2 =$

0.815, adjusted $R^2 = 0.802$, $F = 90.83$, $p < .001$). The model demonstrated a positive correlation with teacher readiness ($B = 0.340$, robust standard error = 0.080, $z = 4.227$, $p < .001$). Considering the other variables in the model, an increase of 10 points in teacher readiness would result in an increase of 3.4 points in sustainable utilisation. School mean student participation was also a positive predictor ($B = 0.554$, robust standard error = 0.176, $z = 3.148$, $p = .002$). This variable was also a participant outcome and facilitated the continued utilisation of the laboratory in education.

Following the additions of readiness and participation, the direct modalities became insignificant in the model. With respect to the physical condition, the coefficient for the virtual and the blended approaches were $B = .472$ ($p = .816$) and $B = 4.120$ ($p = .213$), respectively. Inadequacy of the ICT infrastructure ($B = .042$, $p = .948$) and recent digital training ($B = .841$, $p = .396$) also remained insignificant. The absence of significance of these factors should not be misconstrued to mean that they are not important. It may be that part of their impact is subsumed in the broad construct of readiness and within the condition-specific participation. The main point of the analysis is to show that, given teacher readiness and student participation, the large, unrefined advantage of the blended approach is considerably reduced.

Table 7. Cluster-robust regression predicting sustainable utilisation

Predictor	B	Cluster-robust SE	z	p
Virtual approach (ref: Physical)	0.472	2.034	0.232	0.816
Blended approach (ref: Physical)	4.12	3.307	1.246	0.213
Teacher readiness	0.34	0.08	4.227	<.001
School mean student participation	0.554	0.176	3.148	0.002
Infrastructure adequacy	0.042	0.639	0.065	0.948
Digital training in last 2 years	0.841	0.99	0.85	0.396

Note. Statistics are based on the primary field dataset collected from the sampled schools.

Regarding the assessment of sustainable use, the blended approach was predicted to improve the likelihood of achieving sustainable use in sampled schools. The positive relationship between the blended approach and the likelihood of achieving sustainable use was expected.

The fourth null hypothesis is therefore only partially rejected. Overall, the predictor is statistically significant. However, not all of the coefficients are statistically significant. Mechanism-based thinking provides insight in this case as well. The blended configuration is more acceptable in terms of both the descriptive statistics and analysis of variance because of the more favourable implementation ecology, which includes more prepared teachers and more participating students, and has little to do with the designation of the configuration. The preceding interpretation of the blended configuration is also supported by recent studies. These studies suggest that an emphasis on technology without adequacy in teaching and organisational systems leads to a situation where technologies remain underutilized (Shambare and Jita, 2024; Shambare and Jita, 2025; Na'Allah, 2026).

DISCUSSION

Teacher Readiness and the Meaning of the Blended Advantage

This study found the highest mean level of teacher readiness in the blended condition. It also found the largest overall modal effect in the same condition. It is theoretically valid to interpret teacher readiness as the individual's capacity to function in several pedagogical roles (i.e. pedagogical, digital, technical and safety roles). Blended instruction requires teachers to go beyond the technical skill of running a simulation or performing a hands-on laboratory practical. Blended instruction requires teachers to determine the best virtual activities for teaching and what real-world activities would help students achieve the desired objectives. In addition, teachers must determine the best virtual and real-world activities to achieve the required objectives; and most importantly, how to ensure students' safety in the real world laboratory. Regular engagement with the blended instructional mode strengthens the teacher's professional competence.



This is corroborated by recent research on teacher readiness in Nigeria. Igboanugo (2024) found that when it comes to the integration of digital technologies, readiness is not influenced by gender and other sociological variables. Therefore, in teaching and learning technology integration, the main focus should be on strengthening the teacher's professional development, especially in relation to the integration of ICT in the teaching of Chemistry, and not on the availability of teaching and learning ICT infrastructure. Na'Allah (2026) and Igboanugo, Odimkpa and Dike (2026) held similar positions regarding Chemistry teachers in Anambra State, Nigeria.

This changes how we should construct and choreograph teacher professional development. Short, tool-focused demonstrations will not support teacher professional learning. Teacher professional learning should start with learning the Chemistry and should help teachers understand the pedagogy and the environment to teach that learning. As an example of teaching the pedagogy, teachers can design a virtual activity to engage students in practising the thinking and developing the logic of a titration and teach students the concept of endpoint in a titration. As an example of teaching the practice, the students can learn the concept of meniscus and how to control a burette and practice other skills and precautions related to the experiment. Similar, post-lab virtual activities can be designed to teach students about stoichiometric thinking. Therefore, teacher professional learning should be about the pedagogy and the content. Teacher professional learning should support teachers' competence on design of instruction and integration of technology in teaching. Similar to TPACK, this explains that in order to meaningfully integrate technology in teaching, teachers should have competence on pedagogy and content.

Student Participation Across the Three Approaches

Of the three approaches, blended learning was the highest attracter of student participation with virtual learning coming next, with traditional learning being the least attracter of student participation. One of the reasons could be the presence of active participation opportunities. In face-to-face classes, a lack of adequate equipment and apparatus may restrict active participation to a small number of students in a group. In virtual classes, students have opportunities for repetitive actions, variable alteration, and observation of outcome. For example, in the study conducted by Ezeuduji (2025), the ChemLab activity enhanced participant's engagement. Numerous studies in Nigeria have supported the use of virtual labs to enhance participation and performance in chemical lessons (Onyinye, Egbo and Agujiobi, 2023; Avwiri and Odiri, 2025; Jack and Shidawa, 2025; Akachukwu and Nwankwo, 2026; Anari et al., 2026). From the above studies, the authors believed that the increase in participation and performance was as a result of an increase in opportunities for active student participation.

The result did not in any way mean that the use of virtual classes increase engagement of students as compared to other classes. In one of their studies, Viitaharju et al. (2023) indicated that students' participation in virtual classes was as a result of the previously done preparation. Hence, if a teaching activity requires students to engage in a series of virtual activities, it does not mean that the students have developed an understanding on how to do the virtual activity. In order for students to participate meaningfully in a scientific activity, they must predict outcomes of the activity, manipulate the activity, explain abnormal outcomes and observe or identify evidence that supports their predictions and/or explanations.

The increased participation in the blended condition could be due to the opportunities to engage offered in the different phases of the activity. The virtual environment of the blended programme provides opportunities for rehearsal. Students then engage in the laboratory exercises to further refine the procedures, and may participate in the exercises, which involve the manipulation of equipment. The exercise of physical collaboration provides opportunities for participants to experience the equipment and manipulate it. There are limits to what can be achieved in the virtual environment, and, therefore, the combination of virtual and physical environments is appropriate. The results obtained for the blended condition support the conclusions drawn for the other two conditions regarding the three Nigerian state case studies, also for performance, and confidence levels. Therefore, the findings extend the logic of the authors to include blended condition participation as well.



Sustainable Utilisation as an Organisational Outcome

Sustainable utilisation, of the three outcomes, demonstrated the highest effect size. The difference between the blended and physical conditions was 20.2 points. Continuity is a key component of quality of service, and the blended condition had a more positive impact on continuity. A virtual environment allows for the use of rehearsal to practice a procedure. Consumables, equipment and other resources may be unavailable due to numerous reasons. Rehearsal may be used to sustain what has been learned. Authentic practice should be stressed when possible to ensure that the virtual environment is integrated with practice that is examination related and professionally relevant.

The regression model shows a more plausible interpretation than the straightforward comparison of unadjusted means. Without the control of either teacher readiness or school-level participation, the blended format was statistically significant. This supports a non-tech deterministic interpretation. Sustainability of blended formats must consider participation of students and teaching staff in adequately justifying and supporting the added organisational work. Results therefore suggest that teacher participation and student engagement largely justify the blended format.

This interpretation is generally in line with recently developed education policies in Nigeria. The National Digital Learning Policy encourages integration of digital learning with other allied factors and systems, including teaching and learning quality and accessibility (Federal Ministry of Education, 2023). The National Education Technology Strategy calls for integration of a number of allied factors including governance, and finance (Federal Ministry of Education, 2025). It is expected that similar integration be adopted in the other sub-sectors of education in Nigeria. While adopting a blended learning format in any sub-sector, related factors, including access, teaching and learning, and a wide range of support systems must be ensured.

Physical, Virtual and Blended Approaches Should Not Be Judged on a Single Outcome

The additional outcomes provide additional evidence on the deficiencies of evaluating laboratory modes of operation through a single measure of success. It was found that, while confidence in the correct execution of lab procedures was higher in physical models, understanding of the scientific concepts behind the procedures was higher in virtual models. As expected, the blended model was the most effective for both of these outcomes. This findings corroborate other recent findings in the academic literature. Viitaharju et al. (2023) noted that while students appreciated the opportunity to virtually practice lab procedures, this did not alter their opinion regarding the necessity of performing 'real' laboratory work. On the other hand, Tatenov et al. (2023) and Marino (2026) noted that the use of virtual laboratory work showed positive impact on different forms of abstract thinking and learning.

Based on these results, the best course of action would be to determine the optimal course of action based on the context rather than determine if virtual work is 'better' than physical work. As noted in the recent findings, the use of virtual laboratory work can facilitate various learning situations that require practice and repetition, as well as the exploration of dangerous and/or unpredictable situations. Similarly, physical laboratory work can facilitate practice and repetition of lab procedures as well as encourage and develop laboratory discipline and safety. The best blended models would be those which achieve the greatest integration of virtual and physical work, and are strategically aligned with learning outcomes.

Implications for South-East Nigeria

A regional approach should establish minimum-readiness criteria for schools as primary scaling criteria and ensure equitable procurement of educational materials as a secondary scaling criterion. With respect to teachers, competency-based professional development offered by the ministries/state boards of education of Abia, Anambra, Ebonyi, Enugu and Imo, should be enhanced to assist teachers in designing instructional sequences comprising a virtual pre-laboratory activity, laboratory activity and a post-laboratory activity, diagnose and resolve issues related to the digital platform, use the digital platform and other strategies to teach laboratory activities in case of unreliable Internet access, assess students' practical and conceptual skills, and enhance instructional activities using the digital and physical resources available to them.



Integration of digital and physical resources in an educational setting requires the pragmatism to understand the context. The use of digital and online resources is hinged on the reliability of the Internet. It is important for education stakeholders in this region to understand that the primary goal of digital education is to improve the quality of instruction and not to exacerbate the current education equity gap.

The participation of students needs to be monitored in the context of explicit implementation at this level. Schools can adjust responsibilities, require students to complete pre-laboratory simulation, use short prediction questions, and help students make sense of simulation by incorporating other observable variables, to ensure that students' learning is not fragmented. Schools can make simulated virtual activities integrated with other learning activities to reduce recreational nature of virtual activities and teacher demonstrations in practical activities. Active participation of learners in these learning activities shows a commitment by the schools to sustain the use of the activities in schools.

Sustaining blended learning in schools requires instructional and assessment strategies to support it. Blending involves integrating simulated and physical activities, therefore assessment should integrate both as well to enhance sustainability of blended learning in schools. The evidence collected by simulation and practical activities should be considered jointly. The significance of the evidence should inform the decision on the activity or assessment to be relied upon. For example, evidence collected from the simulation activity should not be considered as proof of students' ability to perform laboratory activities.

When a decision is made to scale a laboratory innovation, it should be carefully evaluated and the process should be complemented with continuous monitoring. A programme should have performance indicators to assess the long term impacts of the programme beyond the installation of equipment or software. A good performance indicator should provide an understanding of the impact of an integrated programme and answer questions such as the ratio of Chemistry teachers who are able to create blended lessons, the proportion of laboratory periods that are delivered, the ratio of students who completed the virtual part of the lesson, the ratio of students who engaged in the practical class, equipment usage and consumption, and how long the equipment is used. Some of these indicators can be tracked and reported through state-level dashboards. These dashboards can assist the Ministry of Education to locate situations where teaching practice deteriorates, and help to localise where infrastructure and support are most required.

LIMITATIONS AND DIRECTIONS FOR EMPIRICAL RESEARCH

Respondents have indicated ways to strengthen the study. Research should evaluate more school clusters and refine stratified sampling for factors such as state, location (urban/rural), school ownership and resource/connectivity. Repeated measurement over several months would strengthen the evidence compared to a one time measurement. Research has indicated ways to strengthen the quality of evidence. Evidence should include various levels of measurement (i.e. teacher and student levels, school levels) and use direct observations to gauge participation. Direct observations should capture measures of student engagement, consumption of resources, and the fidelity of implementation.

Improvements can be made to how mediation is studied and evaluated. Some of the assumptions driving the regression analyses may benefit from additional measures of teacher and student participation over time. Prior studies suggest education innovations may not always be fully affordable, and future studies should consider health, education and economic impacts (i.e. the potential negative implications of increased blended learning). Additional studies should address Deriba, Saqr and Tukiainen's (2024) call to measure participant engagement and accessibility considering factors such as student ability and disability, student gender, student location and student socioeconomic status.

CONCLUSION

This study investigated physical-only, virtual-only and blended physical-virtual Chemistry labs by using the constructs of teacher readiness, student participation and sustainable usage. Field study data showed significant differences in the three conditions for the three main constructs. Of the three conditions, the blended condition



showed the highest mean teacher readiness and participation and sustainable usage. Statistically significant differences were found in all case compared conditions. Effect sizes showed large differences. Physical laboratories developed participants' confidence more than virtual laboratories. The opposite was true for participation. Blended conditions outperformed the other two conditions for both confidence and participation. Thus, virtual laboratories should be used for practices where participants can control the outcome and learn processes while physical laboratories should be used for practices that involve controlling and/or interacting with the environment. Thus, the objective should be to use both physical and virtual laboratories for teaching Chemistry.

Regression analysis indicates that incorporating teacher readiness and student participation as variables improves the model. In the end, the nature of the lecture as a teaching modality did not significantly predict sustained utilisation. However, teacher readiness and student participation did predict sustained utilisation in the model. Thus, from the evidence, sustaining blended learning involves more than infrastructure and technology; it requires teachers who are skilled to blend learning modalities, and students who participate actively to enable teachers to achieve integration of teaching and learning modalities. Sustaining blended learning involves combination of the right technology, pedagogy and infrastructure.

The policy best suited to South-East Nigeria is a contextually flexible, blended-laboratory strategy. Representatives of education ministries and departments at the state level, boards of education, and institutions of teacher education should work in partnership to establish the professional development of teachers at all levels. Teacher educators should take the lead in incorporating simulated laboratories in professional development training. They should restore and maintain on-site physical laboratories, and align and adjust assessment of teachers' ability to integrate practical work in teaching.

Reports from field studies, including the research presented in this article, provides a foundation for additional work. Longitudinal studies, however, involving the entire region and involving larger populations, should be conducted for investigators to reach broader and more generalisable conclusions about research in laboratory science and education in the region.

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Ethical and Data-Integrity Statement

The study collected primary data from selected public senior secondary schools. The identities of the schools and the participants were secured in the researcher's analytical files. This study does not disclose the identities of participants. The researcher will secure and insert in the final copy of the journal, the ethical clearances and relevant approvals of the education and research authorities, the participations of volunteers and the assents of minors.

Conflict of Interest

There is no conflict of interest associated with the author and this work.

Data Availability

An analytical workbook is available and contains secured/anonymised data of Chemistry teachers and Senior Students, other statistical data and codebook. The researcher will secure, administer and control participant's data in accordance with the law and research, educational and academic requirements of the study.



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