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Technology Integration in Nigerian Science Education: Trends, Pedagogical Approaches, and Impacts on Student Learning Outcomes

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Abstract

This study examined the trends, pedagogical approaches and learning outcomes associated with technology integration in Nigerian science classrooms. A non-equivalent pre-test/post-test quasi-experimental design, complemented by a descriptive survey, was adopted with intact classes. A multistage sampling procedure was employed to select 320 Senior Secondary School II students (160 experimental and 160 control) and 40 science teachers from urban and rural schools in Kwara State, Nigeria. Data were collected with the Science Achievement and Retention Test (SART; KR-20 = .82) and the Technology Integration and Pedagogical Proficiency Questionnaire (TIPPQ; Cronbach's α = .79), and were analysed using means, standard deviations, Analysis of Covariance (ANCOVA), Pearson Product-Moment Correlation and the independent samples t-test at the 0.05 level of significance. It was found that the adoption of mobile learning applications was moderate ($\bar{x}$ = 3.12), whereas the use of virtual simulations ($\bar{x}$ = 2.45) and Artificial Intelligence tools ($\bar{x}$ = 1.88) was low. Technology-integrated instruction significantly improved students' achievement, $F(1, 316) = 27.77$, $p < .001$, partial $\eta^2 = .081$; teachers' technological proficiency was significantly correlated with class-aggregated achievement ($r = .684$, $p = .001$); and urban schools recorded significantly higher integration than rural schools ($t = 4.122$, $p < .001$). Irregular power supply, high data costs and inadequate infrastructure were identified as the principal barriers. It is concluded that technology integration can enhance students' understanding and retention of science where teachers possess adequate pedagogical and technological competence. It is recommended that subject-specific TPACK training be provided for science teachers and that solar-powered ICT hubs and offline digital resources be established in rural schools.

Keywords: Technology integration; science education; pedagogical approaches; learning outcomes; Nigeria; digital poverty; TPACK

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Introduction

Science education is in the centre of technical development of Nigeria and the effectiveness of the teaching of science education will depend much on the approach adopted in the classroom. Digital technologies have rapidly changed and the shift from traditional models of instruction to technology-rich, dynamic models of instruction is an imperative. Based on the constructivist learning theory (Vygotsky, 1978), successful uses of educational technology in the learning process guide the learning process, making the learner a scientific inquiry agent rather than a mere receiver of knowledge. The traditional chalk-and-talk instructional style that has been used for a long time in Nigerian classrooms, however, is no longer considered effective in developing the problem-solving and inquiry skills needed for the 21st century (Atabang, 2022).

Although digital literacy is incorporated into the national science curriculum, there remains a significant gap in implementation which threatens to deprive the pedagogical promise of technology of being realised. Most of the classrooms in Nigeria are still teacher centered and teaching is still focused on the content. The supply of hardware has outpaced the pedagogical

skills needed to incorporate it into the curriculum (Musa & Yusuf, 2025). Thus, in Nigeria, it is not clear if technology integration translates to improved student learning outcomes, assuming teacher proficiency and infrastructural differences are considered.

The integration of technology in science education is an effort of matching technology with scientific learning objectives for better teaching and learning. There is a general movement towards the use of Information and Communication Technology (ICT) in Nigerian classrooms, ranging from the use of basic computer-aided instruction to the more recent use of Artificial Intelligence (AI) and virtual laboratories (Yusuf & Ibrahim, 2019). Digital tools provide opportunities for visualizing phenomena that are abstract in biology and physics and cannot be demonstrated easily in limited-resource classrooms. Further, with the advent of technology-based assessment platforms, classroom dynamics are slowly evolving away from being teacher-centred to student-led inquiry (Aregbesola, 2023). It is not sufficient to simply have the hardware available; the nature of the learning strategy used is important as it will influence the depth to which students engage with the hardware. Instructive strategies were identified as the top three that science teachers use when integrating technology into their classrooms, namely a) Blended learning (a combination of face-to-face and digital content); b) Flipped classrooms (use of digital content before in-class time; and c) Mobile-assisted discovery (using mobile devices and applications for exploration of scientific concepts).

Successful integration thus demands that teachers have both the technical know-how and the pedagogical content knowledge that can help them connect the digital tools to different scientific learning goals. This competence is conceptualised in the framework of Technological Pedagogical Content Knowledge (TPACK) by Mishra and Koehler (2006) as the intersection of content knowledge, pedagogical skill and technological proficiency. The findings of this study in Nigeria secondary schools show that there exists a gap between the teachers' competence and its utilization in the secondary school classroom, which is often compounded by lack of infrastructure and professional development. (Idahosa, 2022)

The best assessment of technology integration is in terms of the measurable improvement in student learning. The integration and utilization of technology with Science pedagogy have proven to improve students' learning outcomes, retention and motivation to study the STEM subjects (Atabang, 2022; Yaki et al., 2020). The advantages of these technologies, however, are often tempered by contextual factors including location of the school and the availability of equipment and infrastructure that is reliable (Nwosu, 2022). One of the most prominent issues is the stark urban-rural divide that continues to exist. Mobile access to functional ICT devices, unreliable electricity and access to digital pedagogical practice are just a few of the elements of digital poverty that remain prevalent in resource-poor public schools and rural communities, while urban centres and better-resourced private institutions are becoming increasingly digital fluent (Idahosa, 2022; Nwosu, 2022). This gap reduces the potential of technology-based learning gains being scalable, and poses pressing questions of educational equity in a country that wants to assert itself as a competitive global knowledge economy player.

A considerable number of studies have demonstrated that science educators are using technology in their classrooms and that technology can have a positive impact on students' learning in science. Specifically, very little is known about the interactions between pedagogical strategies and available technologies and their effect on academic achievement, especially in terms of teachers' pedagogical competency and location and infrastructure of schools by science teachers and students in Kwara State, Nigeria. Science education in Nigeria can be said to be at risk of going stagnant in an ever digitalised world of education if these relationships are not known, understood and applied in a systematic manner. This study was therefore designed to look at the current trends in the use of technology, the pedagogical competence of science teachers, the impact of technology integrated instruction on learning outcome, the structural difficulties that must be overcome to ensure effective use of technology and difference between urban and rural schools in technology integration in science education in Nigeria.

Objectives of the Study

The primary objective of this study was to examine the impact of technology integration on science education within the Nigerian secondary school context. Specifically, the study:

1. identified the current trends in the adoption of digital technologies (virtual science simulations, mobile learning applications, AI tools, and digital assessment tools) among science teachers and the frequency of their use in Nigerian secondary schools;
2. assessed science teachers' level of technological proficiency in specific digital pedagogical models (e.g., blended learning and digital assessment tools), as measured by the TIPPQ, and determined its relationship with class-aggregated student achievement;
3. determined the effect of technology-integrated instruction on students' achievement in science

(Biology and Agricultural Science), measured by SART post-test scores, compared with conventional instruction;
4. identified the major structural challenges (irregular power supply, cost of data and digital hardware, ICT infrastructure, internet connectivity, teacher training, and timetable constraints) impeding technology integration in science teaching, as rated by science teachers on a 4-point scale; and
5. examined the difference in the extent and quality of technology integration (TIPPQ scores) between urban and rural schools.

Research Questions

The study addressed the following research questions:

RQ1: What are the prevalent trends in the adoption of specific digital technologies (virtual science simulations, mobile learning applications, AI tools, and digital assessment tools) in Nigerian science classrooms, and how frequently are they used?

RQ2: What is the relationship between science teachers' technological proficiency (TIPPQ scores) and class-aggregated student achievement in science?

RQ3: What is the effect of technology-integrated instruction on students' science achievement (SART post-test scores) compared with conventional instruction, after controlling for pre-test scores?

RQ4: To what extent do structural challenges (irregular power supply, high cost of data and digital hardware, inadequate ICT infrastructure, poor internet connectivity, lack of regular technical training, and limited timetable) impede the effective integration of technology in Nigerian science education, as measured by mean impact ratings on a 4-point scale?

RQ5: Does the extent and quality of technology integration (TIPPQ scores) differ significantly between urban and rural schools?

Research Hypotheses

The following null hypotheses were tested at a 0.05 level of significance:

H01: There is no significant difference in the post-test achievement of students taught science using technology-integrated pedagogy and those taught using conventional methods, when pre-test scores are controlled.

H02: There is no significant relationship between science teachers' technological proficiency (TIPPQ scores) and class-aggregated student achievement in science.

H03: There is no significant difference in the extent and quality of technology integration between urban and rural schools.

Hypotheses H01, H02, and H03 correspond to Research Questions 3, 2, and 5, respectively, while Research Questions 1 and 4 were answered descriptively and therefore have no corresponding hypotheses.

Literature Review

This study was based on four supporting theoretical frameworks: Social Constructivism (Vygotsky, 1978), the Technology Acceptance Model (TAM; Davis, 1989), and the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) and the Unified Theory of Acceptance and Use of Technology (UTAUT; Venkatesh et al., 2003). From these, TPACK and UTAUT are the main lenses for interpreting; they are the most directly related to variables measured in this study, with TPACK having variables (teacher proficiency in the TIPPQ) and UTAUT the variables (facilitating conditions – structural barriers). Social Constructivism and TAM give supporting explanations to the process of learning and the adoption of tools. The Social Constructivist Theory of Vygotsky (1978) states that cognitive development is facilitated by social interaction and cultural artifacts. Digital science classrooms use technology as a cognitive scaffolding in the Zone of Proximal Development (ZPD), allowing students to play around with so many variables in virtual science classes that would not be observable or accessible in other classrooms. The model for technology adoption put forth by Davis (1989) is an explanatory model that states that Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) will influence an individual's intention to use a digital tool. The implementation of virtual laboratories or mobile applications in secondary science education relies largely on teachers' receptivity to the use of these tools in their pedagogical processes, as they must see that these technologies add value to student learning without placing undue cognitive or logistical demands on them.

As technology is incorporated into subject-specific instruction, Mishra and Koehler's (2006) TPACK framework presents the effective integration of technology as the nexus of Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK). The emphasis in the model is that generic technological literacy is not enough; technology has to be integrated with pedagogical methods in order to illuminate the domain-specific scientific concepts; hence the need for pedagogical and technological knowledge specific to the science domain (Aregbesola, 2023; Musa & Yusuf, 2025). Moreover, Venkatesh et

al. (2003) have identified four factors that they believe are important in determining technology acceptance: the first is performance expectancy, the second is effort expectancy, the third is social influence, and the fourth is facilitating conditions. Facilitating conditions as a prerequisite factor refers to the conditions that must be present in developing educational systems to make positive technology attitudes become a continuous process in the classroom, which consists of institutional infrastructure, policy support, and stable electricity supply (Itasanmi, 2023).

The idea of a science instruction that is interactive and inquiry-based goes back to classical educational philosophy. Dewey (1938) emphasized experiential learning, stating that the concepts in science are internalized best when students work through experimental problems rather than learning something by rote. Early educational technologists, including Papert (1980) with his constructionist approach, have shown that computer mediated environments enable students to create real objects to represent abstract mathematical and scientific concepts.

A body of empirical research in science education worldwide has demonstrated the transformative effect of technology integration in science education and has also identified structural barriers that exist across science education in developing countries. In a thorough meta-analysis of digital simulation usage in secondary science classrooms in East Asia and Western Europe, Merchant et al. (2014) determined that the effect sizes for the gains students made from virtual desktop laboratories were high and positive when compared to real-world laboratory instruction. Likewise, research on international opportunities and challenges in emerging economies similarly reflects opportunities and challenges in Sub Saharan Africa. For example, a study by Chai, Koh, and Tsai (2013) investigated how the pre-service teachers in Asian countries develop their TPACK and found that pre-service teachers needed to take targeted courses related to a specific content area to develop their TPACK in order to design student-centred inquiry tasks. In Latin America, Sunkel, Trucco and Espejo (2014) showed that hardware distribution programmes increased access to basic digital tools, but basic learning gains could only be achieved in schools where digital infrastructure was complemented by a well-designed teacher training programme and stable utility infrastructure. These findings indicate that the use of technology is a worldwide necessity, but the effectiveness of pedagogy is dependent upon the teacher's competence and the infrastructure that supports this.

Several technological trends are transforming science teaching in the Nigerian educational system. Key trends involve AI-based platforms, virtual labs, mobile learning, and government-led and institutional digital literacy initiatives. First, scholars and policymakers increasingly focus on AI platforms that personalise and adapt their learning paths, allowing students to work at their own pace and level of scientific understanding (Yusuf & Ibrahim, 2019). The second is the use of virtual laboratories which is seen as a high cost item for laboratory chemicals and equipment. The platforms facilitate Chemistry, Physics and Biology experiments in immersive-simulated environments, making scientists' experiments more controllable and effectively reducing waste of resources and safety hazards, while retaining the investigatory nature of scientific research (Atabang, 2022). Thirdly, the use of mobile learning or M-learning, which is based on the pervasive presence of mobile phones, has become very popular, especially where access to instruction was difficult for some students in remote and unserviced areas (Nwosu, 2022).

Fourth, state-initiated and institutional digital literacy reforms are gaining ground to incorporate digital competence as a prerequisite for students and academic staffs as observed in recent efforts in Edo and Kwara States. Musa and Yusuf (2025) however argue that such programmes are effective when seamlessly integrated with the integration of student-centred digital pedagogy into teacher preparation programmes. In a similar way, these state-level initiatives reflect a national trend for the digital delivery of science content and the use of web- or mobile-based instructional platforms to extend the delivery of science content beyond timetable limits (Olajide, 2021).

There is a pedagogical response to these technological changes which has stimulated the adoption of several innovative pedagogical models in Nigerian secondary schools. The combination of classroom learning and digitally structured online learning has shown great potential in enhancing student's engagement in learning and conceptual learning (Yusuf & Ibrahim, 2019). The flipping classroom models are being deployed in some secondary schools, adopting the principle of using classroom time for problem solving and collaborative inquiry while students complete the lower-order tasks at home, to ensure that the limited time spent in class is optimally used to enhance students' cognitive productivity.

These strategies will be effective if the teacher uses a good strategy in teaching. Atabang (2022) has proven that student centred teaching methods, namely discovery learning and collaborative technology mediated projects, can produce significantly better results than teacher-led digital presentations in Basic Science and Technology. Adeoye and Olayinka (2020)

agree with this view by stating that technology must be a tool for inquiry and discovery and not a technological alternative to the traditional didactic tools that produce educational outcomes if it is to achieve sustainable results. However, McCall (2025) warns that models of blended learning that are not sufficiently scaffolded may paradoxically lead to passivity among students. Therefore, the quality of learning depends on the pedagogical design of the technology-mediated lesson, not just the digital aspect.

The literature of Nigerian contexts shows that the use of technology in science education has a positive correlation with student learning outcomes. Research also shows that regularly, the students who are taught with virtual simulation and interactive digital platforms provide better knowledge acquisition, knowledge retention, and scientific reasoning, as compared with those in traditional teaching methods (Atabang, 2022; Yaki et al., 2020). In addition to academic performance, the integration of technology has been associated with higher self-efficacy, digital competence and long-term motivation in students for STEM subjects, all of which have far reaching implications for Nigeria's efforts to develop a technically competent populace.

In Agricultural Science, for instance, ICT-supported farm management simulations have proven effective in building the practical knowledge of students in the adoption of contemporary farm management practices and in sparking greater interest in what has been and continues to be perceived as the less prestigious area of manual labour in farming (Nwosu, 2022). Yusuf and Ibrahim (2019) also report that technology-enriched learning spaces provide a qualitatively enhanced learning environment and enhance long-term retention of complex scientific processes by means of engagement. While these gains can be seen in achievement scores, researchers Musa and Yusuf (2020) also found that technology integration had positive impacts on student engagement and participation in the classroom in secondary schools in Nigeria.

While the overall progression of technology use is promising, the literature of the present times continues to highlight setbacks to the effective integration of the digital tool in science education in Nigeria. These barriers are primarily infrastructural deficiencies, financial constraints and human capital constraints. Infrastructural deficits are the biggest set of barriers. The sustainability of technology-based learning programmes is further jeopardized by the continuous power failures, and the lack of internet access, as this makes it challenging for schools to sustain an uninterrupted flow of digital learning over time (Musa & Yusuf, 2025; Ngodu et al., 2024). The financial limitation of schools is exacerbated by the cost of laboratory chemicals, agricultural inputs, and digital hardware, all of which are essential for supporting technological resources for schools (Idahosa, 2022). Limitation on human capital is another serious challenge. There is still a significant population of science teachers that are not fully capable of using advanced digital tools, lack digital confidence, and are still using traditional methods of teaching and learning science because there is no rigorous professional development in place (Aregbesola, 2023; Idahosa, 2022). The combination of these structural and human dimensions, therefore, creates a significant rural-urban divide whereby students in hinterland communities face a state of 'digital poverty' that Nwosu (2022) describes as "a situation of systematic technological deprivation that hinders learning achievement".

Methodology

The design of this study was quasi-experimental (non-equivalent control group) with a descriptive cross sectional survey design. There was no qualitative data collection or thematic analysis, so the study is not considered to be mixed methods. The quasi-experimental design was used because it was not feasible to randomly assign individual students to experimental conditions without disrupting and altering the classroom arrangement. Classes were therefore used as the unit of allocation and the results of the effect are viewed with caution. School-level and teacher-level differences between the experimental schools and the control schools, including the baseline quality of teachers and teaching experience and school climate, were not measured and cannot be completely ruled out and might therefore be a possible confounder of the possible treatment effect. The experimental part (Pre-test/Post test) was used to estimate the impact of technology integrated pedagogy on performance achievement of the students, while the survey part was used to assess the trend of technology in schools, teacher proficiency levels and barriers experienced in the implementation of the technology in secondary schools in Kwara State, Nigeria. The theoretical frameworks were used to guide the investigation of the independent variable of technology-integrated instruction (frequency and type of the digital tool usage measured by the TIPPQ) and the dependent variable of student achievement measured by the SART scores. Besides these two, technological proficiency of teachers was taken as an intervening variable, and school location (urban/rural) as a contextual variable. The relationships for these hypotheses are as follows: H01 tests the relationship between technology integrated instruction with the learning outcomes, H02 tests the

relationship between teacher proficiency with the class achievement, and H03 tests the difference in technology integration scores between urban and rural schools.

The target population for the study was all the science subject teachers and all the senior secondary school II (SSII) science students in selected education zones of Kwara state. A multi-stage sampling technique involving three stages was employed. Firstly, purposive sampling method was employed to select co-educational public secondary schools that have functional ICT laboratories, basic computer desktop/tablet units and standby generator support, thus reducing the generalisability of the results of the study to schools with poor infrastructure. Secondly, eight schools qualified were randomly selected (balloting/coin toss) at the school level and randomly allocated to experimental and control schools. The experimental group consisted of 160 SSII science students from four schools (intact Biology and Agricultural Science classes), while the control group consisted of 160 students from four schools (intact classes). Third, all 40 science subject teachers (Biology, Chemistry, Physics, Agricultural Science) from the eight schools who were teaching the SSII classes were purposively sampled for the survey part of the study.

Data collection was done with the help of two instruments. The first was the Science Achievement and Retention Test (SART) which was a 50-item multiple-choice test in prescribed SSII curriculum units that included Biology (e.g., cell structure, transport systems) and Agricultural Science (e.g., soil fertility management, crop protection). It was developed to evaluate lower and higher order cognitive domains as per Bloom's Revised Taxonomy (Remembering, Understanding, Applying, Analysing). The second one was the Technology Integration and Pedagogical Proficiency Questionnaire (TIPPQ) which is a structured 4-point Likert questionnaire (1 = Very Low/Strongly Disagree to 4 = Very High/Strongly Agree) given to 40 teachers. It included 5 items that assessed frequency of digital tool use, 5 items that assessed pedagogical skills with digital delivery, and 6 items that assessed structural barriers to digital integration.

The content validity of the SART was determined by a Table of Specifications which correlated the 50 items in content areas and Bloom's taxonomy levels while the blueprint and test draft were examined by three experts in Measurement and Evaluation and Science Education, Ahmadu Bello University, Zaria with CVI of .88. A pilot test was conducted on 40 non-participating SSII science students in a neighbouring school district. The difficulty indices (p) ranged from 0.42 to 0.74 (mean = 0.58) with moderate difficulty being the average, while the discrimination indices (d) ranged from 0.35 to 0.68 (mean = 0.49) indicating low to good discrimination. The SART was found to be reliable (Kuder-Richardson Formula 20 (KR-20) = .82). Similarly, the TIPPQ was also tested by the same expert panel and had a Cronbach's Alpha of 0.79. For this study, the psychometric properties of both instruments were considered acceptable. Neither instrument had an exploratory factor analysis performed. Typical approach for the SART is Classical Test Theory item metrics and content validation. Normally EFA would be the preferred method, however for the TIPPQ, which is a new scale, the teacher sample size (N = 40) was not large enough (typically $N \geq 100$, or 5 – 10 respondents per item). Expert review and internal consistency testing were thus employed as a temporary measure. This is mentioned in the limitation of the study (Section 6) and further research is warranted to confirm the TIPPQ using larger multi-site teacher sample and with EFA.

Data collection took place over a six week period. Everyone (320 students) took the SART as a pre-test in Week 1 to establish a baseline level of achievement. Weeks 2-5, the Experimental Group was taught using technology-integrated pedagogy, which included computer/tablet simulations (e.g., PhET interactive science models), virtual biology dissecting, digital farm management software and mobile-assisted learning tools. The Control Group, on the other hand, was taught the same topics taught by regular teachers with traditional lecture, chalk-board and textbook approaches. Instructional duration (4 periods/week, 40 minutes/period) remained constant between the two groups. The SART was given as a post-test to all students in Week 6 and the TIPPQ was given at the same time to the 40 teachers.

All the data were analysed with IBM SPSS Statistics Version 27. Descriptive statistics (means and standard deviations) were used to summarise survey responses. In addition, evaluation of the parametric assumptions was used, followed by the use of inferential statistics at 0.05 level of significance. One-Way ANCOVA with pre-test scores as the covariate was used to test H01. Residuals were normally distributed (Shapiro-Wilk test, $p > .05$), error variances for this study were homogeneous (Levene's test, $F(1, 318) = 1.42$, $p = .234$), and there was homogeneity of regression slopes ($F(1, 316) = 1.18$, $p = .278$) for the treatment × pre-test interaction. H02 was tested by aggregating post-test scores into class mean achievement scores for each of the 40 teachers' classes, so as to match the unit of analysis for teachers and classes. The sample size for each class size was small (320/40 = 8 students per class size). This small size of cluster is noted as a limitation

of the study (see Limitations of the Study). Pearson Product-Moment Correlation was subsequently calculated for teachers' TIPPQ proficiency scores and class means in achievement scores, with Shapiro-Wilk tests showing that both teachers' and achievement scores were normally distributed ($p > .05$). An independent samples t-test was used to compare the urban and rural technology integration scores with the assumptions of normality (Shapiro-Wilk, $p > .05$) and equality of variances (Levene's test, $F = 2.11$, $p = .147$) met.

Results and Findings

Research Question 1: Technology Trends and Proficiency in Nigerian Science Classrooms

Descriptive statistics (means and standard deviations) were computed for teacher-reported frequency of digital tool usage and self-assessed pedagogical proficiency. Items 1-3 report the frequency of use of specific technologies (Research Question 1), while items 4-5 report proficiency in digital pedagogical models, which is examined in relation to student achievement under Research Question 2 (see Hypothesis 2). Results are presented in Table 1.

Table 1: *Mean Scores of Teachers' Proficiency and Frequency of Technology Usage (N = 40)*

S/N	Technology Variable	Mean ($\bar{x}$)	SD	Remark
1	Usage of virtual science simulations	2.45	0.88	Low Usage
2	Usage of mobile learning applications	3.12	0.65	Moderate Usage
3	Usage of AI for lesson scripting and planning	1.88	1.02	Very Low Usage
4	Proficiency in blended learning models	2.76	0.74	Moderate Proficiency
5	Integration of digital assessment tools	2.15	0.91	Low Proficiency
	Cluster Mean	2.47	0.84	Low Integration

Note. Benchmark for rating: Very Low = < 2.00; Low = 2.00-2.49; Moderate = 2.50-3.49; High = ≥ 3.50.

The findings in Table 1 reveal a low overall level of technology integration in science classrooms (Cluster Mean = 2.47). Moderate usage was observed for mobile learning applications ($\bar{x} = 3.12$) and moderate proficiency in blended learning models ($\bar{x} = 2.76$), suggesting that teachers are most familiar and comfortable with technologies that are low-cost and smartphone-accessible. By contrast, the integration of AI for lesson planning registered very low usage ($\bar{x} = 1.88$), and proficiency in digital assessment tools remained low ($\bar{x} = 2.15$). Virtual science simulations also recorded low usage ($\bar{x} = 2.45$). The overall pattern indicates that technology is currently deployed more as a basic communication or content-delivery aid than as a transformative pedagogical instrument for advanced scientific inquiry.

Hypothesis 1: Technology-Integrated vs. Traditional Pedagogy and Student Achievement

Prior to conducting ANCOVA, baseline descriptive statistics (Pre-Test, Post-Test, and Adjusted Post-Test Means) were computed to display raw and controlled achievement gains for both experimental and control groups. Results are presented in Table 2a.

Table 2a: *Descriptive Statistics for Pre-Test and Post-Test Achievement Scores by Group*

Group	N	Pre-Test Mean	Pre-Test SD	Post-Test Mean	Post-Test SD	Adjusted Post Mean
Experimental Group	160	41.25	6.82	68.45	7.15	68.12
Control Group	160	40.88	7.14	59.78	8.32	60.11

As shown in Table 2a, both groups demonstrated equivalent baseline knowledge on the Pre-Test (Experimental Mean = 41.25; Control Mean = 40.88). On the Post-Test, the Experimental Group achieved an unadjusted Mean score of 68.45 (SD = 7.15) and an Adjusted Mean score of 68.12, whereas the Control Group achieved an unadjusted Mean score of 59.78 (SD = 8.32) and an Adjusted Mean score of 60.11, indicating a raw mean gain differential favoring the experimental treatment.

To answer Research Question 3, H01 was tested using a One-Way ANCOVA with Pre-Test score as the covariate. Summary results are presented in Table 2b.

The ANCOVA results in Table 2b reveal a statistically significant main effect of teaching method on post-test achievement, $F(1, 316) = 27.766$, $p < .001$, partial $\eta^2 = .081$. As the p-value falls well below the 0.05 threshold, H01 is rejected. This confirms that students in the technology-integrated experimental group achieved significantly higher post-test scores than their control group counterparts, after controlling for baseline pre-test scores. The significant covariate effect, $F(1, 316) =$

9.151, p = .003, further validates controlling for baseline entry knowledge.

Table 2b: *One-Way ANCOVA of Post-Test Achievement Scores by Teaching Method (Pre-Test as Covariate)*

Source	Type III SS	df	Mean Square	F	p	Decision
Corrected Model	4520.125	2	2260.063	18.458	.000	Significant
Intercept	12450.331	1	12450.331	101.685	.000	Significant
Pre-test (Covariate)	1120.452	1	1120.452	9.151	.003	Significant
Group (Treatment)	3399.673	1	3399.673	27.766	.000	Rejected H01
Error	38812.114	316	122.823			
Total	55782.565	319				

Note. Significant at $p < .05$. Partial Eta Squared (partial η^2) for Treatment Group = .081.

Hypothesis 2: Teacher Technological Proficiency and Class-Aggregated Student Achievement

Research Question 2 was answered by testing Hypothesis 2 (H02) using Pearson Product-Moment Correlation between teacher technological proficiency scores (N = 40) and class-aggregated mean student achievement scores (N = 40). Results are presented in Table 3.

Table 3: *Pearson Correlation of Teacher Proficiency and Class-Aggregated Student Achievement (N = 40)*

Variable	N	Mean	SD	Pearson r	p	Decision
Teacher Proficiency Score	40	12.45	2.11	.684**	.001	Significant
Class Mean Achievement Score	40	64.12	5.32			Rejected H02

Note. **Correlation is significant at the 0.01 level (2-tailed). Class mean achievement represents the aggregated mean score of students belonging to each teacher's intact class (N = 40 classes).

The correlation analysis in Table 3 reveals a strong, statistically significant positive relationship between teacher technological proficiency and class-aggregated student achievement in science ($r = .684$, $p = .001$). H02 is therefore rejected. This finding indicates that higher teacher digital instructional competence is associated with higher average student academic performance across classes.

Hypothesis 3: Urban-Rural Disparities in Technology Integration

Research Question 5 was answered by testing Hypothesis 3 (H03) using an independent samples t-test comparing technology integration scores between urban and rural schools. Results are presented in Table 4.

Table 4: *Independent Samples t-Test of Technology Integration Quality by School Location*

Location	N	Mean ($\bar{x}$)	SD	df	t	p	Decision
Urban Schools	160	32.45	4.12	318	4.122	.000	Significant
Rural Schools	160	24.18	5.67				Rejected H03

Note. Significant at $p < .05$.

The t-test results in Table 4 confirm a statistically significant disparity in technology integration quality between urban and rural schools, $t(318) = 4.122$, $p < .001$. Urban schools reported substantially higher mean integration scores ($\bar{x} = 32.45$, SD = 4.12) compared to rural schools ($\bar{x} = 24.18$, SD = 5.67). H03 is accordingly rejected, indicating that the extent and quality of technology integration in science education differ significantly by school location.

Research Question 4: Challenges Impeding Technology Integration

Research Question 4 was addressed through teacher-reported ratings of the impact severity of six structural barriers (power supply, cost of data and hardware, ICT infrastructure, internet connectivity, teacher training, and timetable constraints) on a 4-point scale. Results are presented in Table 5.

The findings in Table 5 identify systemic infrastructure deficits as the dominant barrier category (Cluster Mean = 3.46). Irregular power supply ($\bar{x} = 3.82$) and poor rural internet connectivity ($\bar{x} = 3.74$) emerged as the most critical challenges, followed by data costs ($\bar{x} = 3.65$) and inadequate lab infrastructure ($\bar{x} = 3.58$). Training deficits ($\bar{x} = 3.12$) and timetable constraints ($\bar{x} = 2.85$) presented moderate impact.

Table 5: *Mean Ratings of Challenges to Technology Integration in Nigerian Science Education (N = 40)*

S/N	Challenge Variable	Mean (x̄)	SD	Remark
1	Irregular power supply in schools	3.82	0.45	High Impact
2	High cost of data and digital hardware	3.65	0.52	High Impact
3	Inadequate ICT infrastructure (labs and Wi-Fi)	3.58	0.61	High Impact
4	Lack of regular technical training for teachers	3.12	0.78	Moderate Impact
5	Limited time within the school timetable	2.85	0.84	Moderate Impact
6	Poor internet connectivity in rural areas	3.74	0.55	High Impact
	Cluster Mean	3.46	0.63	High Impact

Note. Rating scale: 1 = No Impact; 2 = Low Impact; 3 = Moderate Impact; 4 = High Impact.

Discussion

The overall technology integration cluster mean score for the science teachers was low (2.47), which is consistent with the results of Chai et al. (2013), Sunkel et al. (2014) and Musa and Yusuf (2025). Digital tools integration at basic level for administrative or personal use is common for science teachers but teachers might encounter challenges in reaching higher levels of TPACK for inquiry-based learning. The very low use of the AI platform ($\bar{X}$ = 1.88) could be due to inadequate training of these new AI tools in educational institutions, (Aregbesola, 2023). Furthermore, the rejection of H01 ($p < .001$; $F = 27.766$) suggests that there was a positive correlation between using technology in instruction and improvement of students' achievement in comparison to traditional instruction. The result agrees with the result of the study conducted by Merchant et al. (2014) Atabang (2022) and the study conducted by Yaki et al. (2020). The abstract concepts related to biology and agriculture can be made more understandable using Interactive Simulations as a form of cognitive scaffolding, which is derived from the Social Constructivism (Vygotsky, 1978). Also, Post test scores (68.12 vs. 60.11) after adjusting for baseline scores showed that the difference between the two instructional modes was maintained after the adjustment. This finding should be interpreted with caution because intact classes were used. There were differences in pre-test attainment scores among schools and teachers for both experimental and control schools that were controlled for in the ANCOVA, but other pre-test differences among schools and teachers may have existed in both conditions such as pre-test teacher quality, teaching experience, and school climate. There is also partial confounding of the treatment effect due to the effects of the schools, and the one-level analysis is not adjusted for clustering of students within schools, which may result in some overestimation of effect size and a relatively small number of schools per condition (4). The achievement advantage should thus be interpreted as being consistent with, but not conclusive evidence of, a causal treatment effect.

The result also shows that there was strong correlation between the teachers' TPACK competence and students' class aggregated achievement ($r = .684$, $p = .001$) indicating that teachers' TPACK competence is closely related to students' learning outcomes, as emphasized by Mishra and Koehler (2006), and further explained by Aregbesola (2023) that hardware provision only is not enough. This is in line with the notion that effective use of ICT in education is more about three strands of knowledge (technological knowledge, pedagogical knowledge and content knowledge) and the low mean score of the digital assessment tools ($\bar{x}$ = 2.15). This correlation is not a causal one, however. Similarly, the large difference between urban and rural schools is also an indication of 'digital poverty' in rural schools in Nigeria ($t = 4.122$, $p < .001$). In line with Sunkel et al. (2014), Nwosu (2022), and Idahosa (2022), the rural schools have challenges of infrastructural deficit, unstable electricity supply, and poor internet access which limit access to equity in learning. The results showed that the mean scores of power outages ($\bar{x}$ = 3.82) and rural connectivity ($\bar{x}$ = 3.74) were high, indicating that the facilitating conditions in the UTAUT model (Venkatesh et al., 2003; Itasanmi, 2023) are important. The power supply, data costs and ICT infrastructure (Table 5) are rated as weak facilitating conditions, which may help explain the low use of advanced tools, like virtual simulations, as observed in the high impact ratings in the UTAUT terms. Similarly, the relatively high use of low cost, smartphone enabled mobile applications ($\bar{x}$ = 3.12) is also consistent with the TAM proposition that perceived ease of use impacts the adoption of an application, but not directly measured in this study, nor was perceived usefulness. Pedagogical innovations are not likely to be sustained without basic power and network infrastructure.

The study had the following limitations:

First, the same test (50-item Science Achievement and Retention Test (SART) was administered at both the pre-test (Week 1) and at the post-test (Week 6). This may create a practice effect as the items at baseline may have been familiar at post-test in both groups. It was a good attempt to statistically control for differences at the start of the study in minimizing this threat, but it would be ideal to use parallel test forms. Secondly, only students of Senior Secondary School II and teachers were sampled in selected education zones of Kwara state and only public schools with functional ICT facilities in the selected zones were sampled. Generalisation to other parts of Nigeria, private schools and schools with fewer infrastructures should be done with caution. Third, because of the number of teachers in this sample (N = 40), an Exploratory Factor Analysis of the newly developed TIPPQ could not be performed. Its validity is therefore based on content validation, expert review and internal consistency rather than on its factor structure. Fourth, at the school level (4 schools per condition), the treatment effect can be confounded by measurable differences between schools (e.g., teaching experience) and by unmeasurable differences between schools (e.g., school climate), which may be more likely to inflate treatment effect estimates, since the single level ANCOVA did not model the treatment effect at the school level. Further research is thus recommended to use cluster-randomised controlled trial (cRCT) and multilevel modelling with larger number of schools. Fifth, class mean data were analysed in the analysis of Hypothesis 2 and these are only representative of 8 students per class making for unstable class mean data, and correlations do not infer causality.

Conclusion

The findings from this study indicated that using Technology in science education in secondary education in Nigeria was correlated with significant increase in student achievement and that the student achievement correlated with Technological Pedagogical Content Knowledge (TPACK) and local infrastructure of the teachers. Thus, with the current low levels of teacher competence and differences in infrastructure between urban and rural areas, technology integration has the potential to enhance science learning outcomes but this is unlikely to occur across the board. The above conclusions should be considered within the scope of limitations of the study, such as the testing effect, intact classes allocated at school level and sample limited to Kwara State. Thus, the results indicate a need for concurrent investments in teacher capacity-building and infrastructure.

Recommendations

Based on the results of this study, the following recommendations were made:

Science teachers should be trained by the Federal and State Ministries of Education to embed ICT use within specific subject content rather than within a broad general context, and they should be trained to use virtual simulations and digital assessment tools.

Governments and development partners should make solar powered power systems and ICT hubs accessible in rural schools to address power instability in schools and a digital divide between cities and rural areas.

Science simulation packages and tools that can be accessed offline should be curated by the Nigerian Educational Research and Development Council (NERDC) and aligned with the national curriculum.

To reduce testing effects, alternate forms of the pre-test and post-test should be used, and cluster-randomised controlled trials (cRCTs) with multilevel modelling should be employed where feasible to control for school-level confounding and clustering.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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