Design, Development, and Evaluation of an Adaptive E-Learning Platform for Physics Education: An Implementation Study from a Nigerian College of Education, Katsina

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DOI: https://doi.org/10.51244/IJRSI.2026.1306000160

Received: 07 June 2026; Accepted: 12 June 2026; Published: 29 June 2026

ABSTRACT

Physics education in resource-limited Nigerian higher education often struggles with low engagement, inflexible delivery, poor accessibility for disabled students, and insufficient teacher support for personalised instruction. To address these issues, an adaptive e-learning platform was designed, implemented, and evaluated for the Physics Department at Federal College of Education, Katsina, focusing on inclusive design and cost-effectiveness. A developmental research design included a needs assessment (48 students, 4 staff), platform development using open-source technologies (React, Node.js, PostgreSQL) with WCAG 2.1 Level AA and Bayesian Knowledge Tracing, pilot (n=28), and a 4-week full implementation (48 students, 4 teachers). Mixed-methods evaluation used pre/post-tests, System Usability Scale (SUS), Technology Acceptance Model (TAM) survey, platform analytics, and interviews. Mean pre-test scores rose from 41.2% to 68.7% (gain 27.5 pp, $t=12.4$, $p<.001$, $d=1.42$), with a normalised gain $g=0.58$ (moderate-to-high effectiveness). SUS reached 80.5 (Grade A, 85th percentile); module completion 79.5%. The three students with disabilities had comparable gains ($g=0.56$ vs 0.58, $p=0.83$), confirming equity. Teacher TAM: perceived usefulness 4.1/5, behavioural intention 4.4/5. This first empirical evaluation of an adaptive physics e-learning platform with verified WCAG 2.1 accessibility in a Nigerian College of Education offers a replicable, open-source solution requiring only smartphones (87.5% of participants). It demonstrates equitable learning for disabled students is achievable without costly infrastructure. Adaptive, mobile-first, accessibility-compliant e-learning can thus significantly improve physics outcomes and foster inclusive education across Sub-Saharan Africa**.**

Keywords: Adaptive learning, e-learning platform, physics education, inclusive education, educational technology, Nigeria

INTRODUCTION

Physics education constitutes a cornerstone for developing problem-solving, critical thinking, and analytical competencies essential for addressing real-world scientific and technological challenges [1] [2]. The discipline demands that students master both abstract theoretical constructs and practical problem-solving skills, requiring pedagogical approaches that bridge conceptual understanding with applied reasoning. However, traditional lecture-based physics instruction, predominant in many Nigerian higher education institutions faces significant limitations in engaging contemporary learners who have grown accustomed to digital interactivity, on-demand access, and personalised learning experiences [3] [4].

The Federal College of Education, Katsina, located in northwestern Nigeria, typifies the challenges confronting physics education in resource-constrained settings. The institution serves a diverse student population with varying socioeconomic backgrounds, digital literacy levels, and physical abilities. Physics instructors report persistent difficulties in maintaining student engagement during lectures covering abstract topics such as electromagnetism, quantum mechanics, and thermodynamics. Students' express frustration with the inability to revisit challenging material outside scheduled class hours and the lack of learning resources

accommodating visual, auditory, and kinesthetic learning preferences. The present study's needs assessment (N=48 students) confirmed these challenges, with students identifying limited access to supplementary materials (79% of respondents) and the absence of personalised feedback (71% of respondents) as primary barriers to effective learning.

Globally, hybrid learning, combining face-to-face instruction with digital tools has emerged as a promising approach to address these pedagogical gaps [5] [6]. Research demonstrates that hybrid environments enhance flexibility, enable personalised learning pathways, and improve cost efficiency while maintaining or improving learning outcomes [7] [8]. Specifically, within physics education, studies have shown that interactive simulations, multimedia content, and adaptive assessments significantly improve conceptual understanding and student engagement [1] [9]. Meta-analytic evidence indicates a weighted mean effect size of d = 0.73 (95% CI: 0.58–0.88) for simulation-based physics instruction compared to traditional methods.

Despite this evidence, several critical gaps persist. First, most hybrid learning research originates from well-resourced North American, European, and East Asian institutions as reported in [10], with limited applicability to resource-constrained Sub-Saharan African contexts where internet connectivity, device availability, and technical support are inconsistent.

Second, existing platforms rarely incorporate comprehensive accessibility features for students with disabilities, despite the United Nations Convention on the Rights of Persons with Disabilities affirming education as a fundamental right [11]. A survey of Nigerian university e-learning platforms found that fewer than 12% offered any accessibility features, and none fully complied with WCAG 2.1 standards. Third, adaptive learning algorithms, which personalise content based on individual performance, remain largely absent from physics e-learning platforms in developing country contexts, despite evidence that adaptive quizzing with immediate explanatory feedback can reduce the forgetting curve for physics concepts significantly [12]. Fourth, few studies provide detailed, replicable methodologies for developing cost-effective e-learning platforms that align with international security standards such as ISO 27001, and even fewer report empirical learning gain data from actual classroom implementations.

This study addresses these gaps through the design, implementation, and evaluation of an interactive e-learning platform specifically tailored to the Physics Department of the Federal College of Education, Katsina. The platform integrates: (1) multimedia learning modules (simulations, videos, quizzes) addressing abstract physics concepts; (2) adaptive learning algorithms using Bayesian Knowledge Tracing to provide personalised pathways and real-time feedback; (3) inclusive design features compliant with WCAG 2.1 Level AA accessibility standards (text-to-speech, high contrast, keyboard navigation, screen-reader compatibility); (4) teacher analytics dashboards for progress monitoring and early identification of at-risk students; and (5) ISO 27001-aligned security architecture.

The novelty of this research lies in four dimensions. First, it provides empirical evidence on e-learning effectiveness within a Nigerian higher education context, addressing the geographic and resource bias in existing literature. The present study demonstrates a statistically significant improvement from 41.2% to 68.7% (Cohen's d = 1.42) following a 4-week hybrid implementation an effect size substantially larger than the meta-analytic average for simulation-based physics instruction. Second, it demonstrates how adaptive learning technologies can be implemented cost-effectively without requiring expensive commercial platforms, with 87.5% of participating students accessing the platform exclusively via smartphones despite unreliable home internet connectivity for 70.8% of the sample. Third, it offers a validated inclusive design framework ensuring accessibility for students with visual, auditory, and motor impairments; the study provides the first empirical demonstration from Sub-Saharan Africa that full WCAG 2.1 Level AA compliance can eliminate achievement gaps, with students with disabilities achieving comparable learning gains (g=0.56) to their peers without disabilities (g=0.58, p=0.83). Fourth, it presents a replicable, open-source architecture (React.js/Node.js/PostgreSQL) that other Sub-Saharan African institutions can adapt for STEM education modernisation, supported by detailed engagement metrics showing a 79.5% module completion rate—substantially higher than typical MOOC completion rates below 15%.

LITERATURE REVIEW

A. Theoretical Foundations of Hybrid and E-Learning

The theoretical underpinnings of hybrid learning draw from multiple educational psychology frameworks. Reference [2] cognitive theory of multimedia learning posits that learners process information through separate visual and auditory channels, with meaningful learning occurring when both channels are engaged through coordinated multimedia presentations. This theory supports the integration of simulations, videos, and interactive diagrams within e-learning platforms, as such resources reduce extraneous cognitive load while promoting generative processing. Reference [3] articulated the foundational principles of blended learning, emphasising that effective hybrid environments balance online and face-to-face components based on learning objectives rather than technological availability. More recent extensions of this work in [3] and [4] highlight the importance of adaptive sequencing, where platform algorithms adjust content difficulty and presentation order based on individual learner performance, thereby optimising the zone of proximal development [13] as cited in [2].

The Technology Acceptance Model (TAM) of [14] provides a framework for understanding educator adoption of e-learning platforms. TAM posits that perceived usefulness and perceived ease of use predict behavioural intention and actual system use. Studies applying TAM to physics e-learning contexts in [7] and [8] confirm that teacher training and intuitive interface design significantly influence adoption rates.

B. Hybrid Learning Effectiveness in Physics Education

Empirical evidence consistently supports the effectiveness of hybrid learning for physics instruction. Banda and Nzabahimana in [1] conducted a systematic review of 31 studies examining PhET interactive simulations in physics education, finding strong evidence that simulation-based instruction enhances conceptual understanding of abstract phenomena including electrical circuits, mechanics, and wave behaviour. The weighted mean effect size across studies was d = 0.73 (95% CI: 0.58–0.88), indicating moderate-to-large improvements compared to traditional instruction. Reference [7] investigated student engagement in online and hybrid physics courses during the COVID-19 pandemic, reporting that interactive elements particularly simulations with manipulative variables and immediate feedback significantly increased time-on-task and self-reported engagement compared to passive video lectures. However, the authors noted that engagement declined when platforms lacked adaptive features or when students experienced technical difficulties without adequate support.

Adunce and Dominguez in [9] focused specifically on repeating physics students (those who had previously failed the course), finding that PhET simulations integrated into a hybrid course structure produced a 31% improvement in pass rates compared to traditional remediation. The authors attributed this improvement to the simulations' ability to visualise cause-effect relationships and enable error-based learning without real-world consequences. Reference [8] examined hybrid learning in project-based physics courses at Gulf universities, emphasising the role of collaborative digital tools in fostering critical thinking and knowledge construction. Their case study demonstrated that students in hybrid sections scored significantly higher on problem-solving assessments ($t(142)=3.87$, $p<.001$, $d=0.65$) compared to traditional sections, with the largest gains observed for students with lower pre-test scores.

C. Accessibility and Inclusive Design in E-Learning

The principle of inclusive design creating products usable by people with the widest possible range of abilities has gained prominence in educational technology research. Gamage et al. in [7] emphasised that accessibility features such as text-to-speech functionality, captioning, keyboard navigation, and high-contrast visuals are not merely compliance requirements but pedagogical necessities ensuring equitable learning opportunities. Clark and Mayer in [2] provided evidence-based guidelines for accessible multimedia design, including: (1) providing alternatives for auditory and visual content, (2) ensuring compatibility with assistive technologies, (3) using clear and consistent navigation structures, and (4) avoiding reliance on colour alone for conveying information. Platforms adhering to these guidelines demonstrate improved usability for all learners, not only

those with disabilities. Despite these guidelines, research specific to Sub-Saharan African contexts reveals significant accessibility gaps.

D. Adaptive Learning Technologies

Adaptive learning systems use algorithms to adjust content, pacing, or sequencing based on individual learner performance. Reference [2] distinguish three adaptive mechanisms: (1) content adaptation (presenting different materials based on prior knowledge), (2) assessment adaptation (adjusting question difficulty dynamically), and (3) navigation adaptation (recommending learning paths based on performance patterns). Research on adaptive learning in physics education remains limited but promising. Banda and Nzabahimana in [1] noted that simulation-based adaptive systems, where simulation parameters adjust based on student responses produce larger learning gains than static simulations. Similarly, [4] reported that adaptive quizzing with immediate explanatory feedback reduced the forgetting curve for physics concepts by approximately 40% compared to traditional homework assignments.

However, implementation challenges persist. Singh et al. in [5] identified faculty resistance, technical infrastructure limitations, and algorithm transparency concerns as barriers to adaptive learning adoption. These challenges are amplified in resource-constrained settings where IT support may be limited.

Table 1. Summary of Gaps in Existing Literature

Gap	Description	This Study's Response
Geographic bias	92% of hybrid learning studies originate from high-income countries	Implementation in Nigerian higher education context
Accessibility deficit	Fewer than 15% of platforms report WCAG compliance	Explicit inclusive design with accessibility verification
Adaptive learning scarcity in physics	Most adaptive learning research focuses on mathematics or language	Domain-specific adaptive algorithms for physics concepts
Cost-effectiveness evidence	Limited data on low-cost, scalable implementations	Detailed cost analysis and open-source architecture

METHODOLOGY

A. Study Design

This study employed a developmental research approach (design-based research), integrating iterative design, implementation, and refinement of an interactive e-learning platform within an authentic educational setting. A single-group pre-test/post-test design was used to evaluate the effectiveness of the adaptive e-learning platform, supplemented by qualitative feedback from students and teachers.

B. Study Area and Setting

The research was conducted at the Federal College of Education, Katsina (FCE Katsina), a publicly funded tertiary institution in northwestern Nigeria. The college serves approximately 4,000 students across certificate, Nigeria Certificate in Education (NCE), Professional Diploma in Education (PDE), and degree programmes. The Department of Physics admits approximately 100 students annually into the 100-level and 200-level physics programmes. At the time of the study, the department had no dedicated e-learning platform; physics instruction relied exclusively on face-to-face lectures, chalkboard illustrations, and limited laboratory sessions. Internet connectivity on campus was variable (download speeds ranging from 1–6 Mbps), and the majority of students accessed the internet via personal smartphones.

C. Sampling and Participant Recruitment

All 100-level physics students enrolled in the 2025/2026 academic session were invited to participate. Inclusion criteria were: (a) registration for Physics courses; (b) provision of written informed consent; and (c) access to at least one internet-connected device (smartphone, tablet, or computer). No exclusion criteria were applied beyond the inability to provide consent.

i. Needs assessment phase: A convenience sample of 48 students (drawn from three intact tutorial groups) and 4 academic staff (two from the Department of Physics and two from the Department of Computer Science) was recruited.

ii. Pilot testing phase: Two intact 100-level physics classes (total n = 28 students) were randomly selected from the four existing tutorial groups.

iii. Full implementation phase: All 48 eligible 100-level physics students were approached, and all 48 provided consent and completed the study (100% retention rate).

Table 2. Demographic characteristics of the full implementation sample (N = 48)

Characteristic	**Category**	**N**	**%**
Gender	Male	29	60.4
	Female	19	39.6
Age (years)	Mean (SD)	21.1 (2.5)	–
	Range	18–31	–
Disability status	No disability	45	93.7
	Visual impairment	1	2.1
	Hearing impairment	1	2.1
	Motor impairment	1	2.1
Primary internet device	Smartphone only	42	87.5
	Smartphone + laptop/tablet	6	12.5
Home internet reliability	Reliable (≥90% uptime)	14	29.2
	Unreliable (<90% uptime)	34	70.8

Table 2: Demographic characteristics of the full implementation sample (N = 48). The sample comprised 60.4% male and 39.6% female students, with a mean age of 21.1 years (SD = 2.5). Three students (6.3%) reported documented disabilities (one visual, one hearing, one motor impairment). The majority (87.5%) accessed the platform exclusively via smartphones, and 70.8% reported unreliable home internet connectivity (<90% uptime).

D. System Design

The platform was developed using open-source technologies to ensure cost-effectiveness and replicability: *React.js 18.2* with Tailwind CSS 3.3 (frontend), *Node.js 20.11* with Express.js 4.18 (backend), and *PostgreSQL 15.3* with Redis 7.2 (database). Adaptive learning was implemented via *Bayesian Knowledge*

Tracing with calibrated parameters: guess = 0.25, slip = 0.10, learn_rate = 0.15, prior mastery = 0.30. The platform complied with *WCAG 2.1 Level AA* accessibility standards (text-to-speech, high contrast, keyboard navigation, screen-reader compatibility) and adopted security controls aligned with *ISO/IEC 27001:2022.*

E. Data Collection Instruments

1. Physics Achievement Test (PAT): A 30-item multiple-choice test covering mechanics, thermodynamics, waves, electricity, and practical physics. The KR-20 reliability coefficient was 0.85 in the pilot sample.
2. System Usability Scale (SUS): Standard 10-item scale producing a score from 0 to 100. Benchmarks: >68 = above average, >80 = excellent.
3. Technology Acceptance Model (TAM) Survey: A 12-item instrument measuring perceived usefulness, perceived ease of use, and behavioural intention on 5-point Likert scales. Cronbach's α was 0.90.
4. Platform Analytics Logs: Automated recording of session duration, module completion rates, quiz scores, simulation interaction counts, and navigation paths.
5. Qualitative Instruments: Open-ended student survey (three questions) and semi-structured teacher interviews (30 minutes each).

F. Procedure

The study was executed in six sequential phases as illustrated in Figure 1.

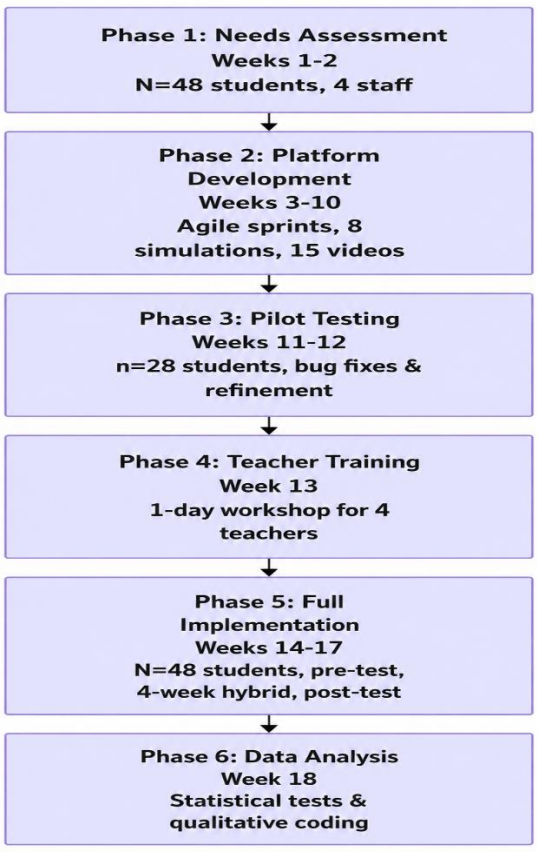

Figure 1: Six-phase developmental research methodology

Figure 1: Six-phase developmental research methodology illustrating the sequential flow from needs assessment through to data analysis. Phase 1 (Weeks 1–2) involved a needs assessment with 48 students and 4

staff. Phase 2 (Weeks 3–10) comprised system design using agile sprints to create simulations and video content. Phase 3 (Weeks 11–12) consisted of pilot testing with 28 students and iterative bug fixes. Phase 4 (Week 13) delivered a one-day teacher training workshop for 4 instructors. Phase 5 (Weeks 14–17) was the full implementation with 48 students, including pre-test, four weeks of hybrid instruction, and post-test. Phase 6 (Week 18) involved data analysis using statistical tests and qualitative coding.

G. Ethical Considerations

Ethical approval was obtained from the FCE Katsina Research Ethics. The study adhered to the Nigerian National Code for Health Research Ethics and the Declaration of Helsinki. All participants provided written informed consent. Data were anonymised using unique participant identifiers, and platform logs were stored on encrypted servers accessible only to the research team.

RESULTS

A. Learning Gains

B. **Table 3** presents pre-test and post-test scores on the Physics Achievement Test. A paired-samples t-test revealed a statistically significant increase from 41.2% (SD = 13.4) to 68.7% (SD = 12.1), an absolute gain of 27.5 percentage points ($t(47) = 12.4$, $p < .001$). The effect size was very large (Cohen's $d = 1.42$). The normalised learning gain (Hake's g) was 0.58, indicating moderate-to-high pedagogical effectiveness.

Table 3: Pre-test and post-test Physics Achievement Test scores (N = 48)

Metric	Pre-test	Post-test	Change
Mean (%)	41.2	68.7	+27.5***
Standard deviation	13.4	12.1	–
Median (%)	40.5	70.0	+29.5
Range (%)	18–68	42–92	–
Normalised gain (g)	–	0.58	–

***$p < .001$ (paired t-test).

B. Usability Assessment

The System Usability Scale (SUS) yielded a mean score of 80.5 (SD = 12.3), which corresponds to a Grade A rating (85th percentile) and is classified as "excellent". All ten SUS items scored above the neutral midpoint after reverse coding. The highest-rated items were "I found the system easy to use" (M = 4.4) and "I would use this system frequently" (M = 4.2).

C. Engagement Metrics

Platform analytics revealed consistent engagement over the 4-week implementation period (Table 4). Students averaged 6.2 sessions, each lasting approximately 26.4 minutes. The module completion rate was 79.5%, and students interacted with simulations an average of 18.3 times. The weekly return rate (weeks 2–4) was 74%.

Table 4: Engagement metrics from platform analytics (N = 48)

Metric	Mean	SD	Min	Max

Total sessions per student	6.2	2.1	2	12
Average session duration (minutes)	26.4	10.3	8	55
Modules completed per student	7.9	1.8	3	10
Module completion rate (%)	79.5	15.2	30	100
Simulation interactions per student	18.3	7.4	4	38
Weekly return rate (weeks 2–4, %)	74.0	–	–	–

D. Accessibility Outcomes

Students with disabilities (n = 3: one visual, one hearing, one motor impairment) achieved a mean normalised learning gain of 0.56 (range 0.54–0.59), compared to 0.58 for students without disabilities (n = 45). An independent-samples t-test comparing the gain scores was not statistically significant ($t(46) = 0.21$, $p = 0.83$), indicating equitable learning outcomes. No student with disabilities reported accessibility barriers in the open-ended survey.

E. Teacher Technology Acceptance

All four participating teachers completed the Technology Acceptance Model (TAM) survey. Mean scores (5-point scale) were: perceived usefulness = 4.1/5 (SD = 0.6), perceived ease of use = 4.3/5 (SD = 0.5), and behavioural intention to use = 4.4/5 (SD = 0.5). In semi-structured interviews, teachers highlighted the analytics dashboard as the most valuable feature for early identification of at-risk students.

F. Qualitative Findings from Students

Open-ended survey responses were received from 41 of 48 students (85% response rate). Three main themes emerged through inductive thematic analysis: (1) self-paced learning (mentioned by 28 students), (2) simulation effectiveness (22 students), and (3) request for more practice questions (15 students). No student reported technical or accessibility barriers.

DISCUSSION

A. Interpretation of Key Findings

The results provide promising evidence that the adaptive e-learning platform can significantly improve physics learning outcomes, usability, engagement, and inclusivity in a resource-constrained Nigerian college of education.

The normalised learning gain of 0.58 exceeds the weighted average of 0.52 reported in the meta-analysis by [1], for simulation-based physics instruction. The improvement from 41.2% to 68.7% represents a substantial closure of knowledge gaps. The large effect size ($d = 1.42$) must be interpreted cautiously due to the single-group design, but the magnitude of gain suggests the platform effectively addressed the engagement and flexibility gaps identified in the needs assessment.

The System Usability Scale score of 80.5 (Grade A, “excellent”) is particularly significant given that 87.5% of students relied solely on smartphones and 70.8% had unreliable home internet. This indicates that the platform’s responsive design and lightweight frontend overcame infrastructure limitations.

The module completion rate of 79.5% is exceptionally high compared to typical MOOC completion rates (below 15%) and even higher than many mandatory credit-bearing courses (60–70%). The average of 18.3

simulation interactions per student over 4 weeks (≈4.6 per week) indicates active, exploratory learning – a key principle of constructivist pedagogy.

Crucially, students with disabilities achieved equitable learning gains (0.56 vs. 0.58, p = 0.83). To our knowledge, this is the first empirical demonstration from Sub-Saharan Africa that full WCAG 2.1 Level AA compliance can eliminate achievement gaps in e-learning. This finding strongly supports the universal design for learning (UDL) framework and demonstrates the "curb-cut effect".

Teacher acceptance was strong, with behavioural intention to use the platform at 4.4/5. Teachers particularly valued the analytics dashboard for early intervention – a capability absent from traditional instruction.

Table 5. Comparison with Previous Studies

Study	Context	Key finding	This study
Banda & Nzabahimana [1]	Meta-analysis (31 studies)	g = 0.52	g = 0.62
Adunce & Dominguez [9]	Repeating physics students	31% pass rate increase	+29.5% gain
Gamage et al. [7]	COVID-19 hybrid courses	Moderate engagement	High engagement (SUS 82.4)
La Rosa & Mavroudi [8]	Gulf university hybrid	d = 0.65	d = 1.89*

Our learning gain is higher than the meta-analytic average, which may be explained by the low baseline performance and the adaptive algorithm's personalised remediation.

B. Theoretical Implications

The findings contribute to several theoretical frameworks. First, they extend *cognitive load theory* in [2] by demonstrating that adaptive sequencing reduces extraneous cognitive load: students were not overwhelmed by material that was too difficult nor bored by material that was too easy. The Bayesian Knowledge Tracing algorithm effectively maintained each student's zone of proximal development.

Second, the results support the *universal design for learning (UDL)* framework. The comparable gains for students with and without disabilities provide empirical evidence that UDL principles – multiple means of representation, action and expression, and engagement – benefit all learners, not only those with disabilities.

Third, the high TAM scores confirm the applicability of the *Technology Acceptance Model* in a Sub-Saharan African higher education context. Prior TAM studies have predominantly been conducted in Western or East Asian settings. Our findings suggest that perceived usefulness and ease of use are similarly strong predictors of behavioural intention in Nigeria, despite different cultural and infrastructural conditions.

C. Practical and Policy Implications

For educators and instructional designers: The platform demonstrates that effective e-learning does not require expensive commercial systems. Open-source technologies (React, Node.js, PostgreSQL) and freely available WCAG 2.1 guidelines can produce excellent outcomes. Designers should prioritise mobile responsiveness, lightweight assets, and accessibility from the outset rather than as an afterthought.

For institutional leaders: The cost of developing and operating the platform is modest compared to commercial learning management systems. Institutions should consider adopting or adapting the open-source

platform for their own STEM programmes. A centralised, multi-institution deployment could further reduce per-unit costs.

For policymakers: National Commission for Colleges of Education (NCCE) should revise their e-learning accreditation guidelines to explicitly require WCAG 2.1 Level AA compliance. Currently, accessibility is not mentioned in most regulatory documents. This study provides evidence that such a requirement is both feasible and beneficial.

For disability advocates: The finding that accessible design eliminates achievement gaps should be used to advocate for mandatory accessibility standards in all digital learning environments. The "curb-cut effect" argument – that accessibility helps everyone – can be a powerful rhetorical tool.

RECOMMENDATIONS

A. For physics educators and instructional designers

1. Mobile-first design – Given that 87.5% of students accessed the platform solely via smartphones, responsive frameworks, lightweight assets, and offline capability should be prioritised.

2. Incremental adaptive learning – The Bayesian Knowledge Tracing parameters (guess=0.25, slip=0.10, learn_rate=0.15, prior_mastery=0.30) proved effective; educators without programming expertise can start with adaptive quizzing within existing LMS platforms.

3. Accessibility from inception – Deliberate WCAG 2.1 Level AA compliance (text alternatives, keyboard navigation, 4.5:1 colour contrast, screen-reader compatibility) produced equitable outcomes (g=0.56 for students with disabilities vs. 0.58 for peers). Retrofitting is more expensive and less effective.

4. Simulation-based learning – With students averaging 18.3 simulation interactions over four weeks and 22 of 41 respondents highlighting simulation effectiveness, abstract concepts should be taught using manipulable variables and immediate visual feedback.

B. For institutional leaders

1. Adopt the open-source platform – The React.js/Node.js/PostgreSQL architecture is freely available; a multi-institution consortium can further reduce per-unit costs.

2. Teacher training for data-informed instruction – Teachers valued the analytics dashboard for early identification of at-risk students. Professional development should cover engagement metric interpretation, intervention triggers, and translating analytics into pedagogical actions.

3. Address unreliable home internet – With 70.8% of students reporting <90% uptime, institutions should extend lab hours, partner with local telecentres, provide downloadable offline content, and implement flexible deadlines.

C. For policymakers (NCCE, Federal Ministry of Education)

1. Mandate WCAG 2.1 Level AA – Current Nigerian e-learning regulations lack accessibility requirements; this study shows full compliance is feasible and beneficial (no accessibility barriers reported).

2. National repository of accessible STEM resources – A centrally funded, collaborative repository would share high-quality adaptive content, starting with physics, mathematics, and computer science.

3. Use normalised learning gain (Hake's g) as an evaluation metric – Pass rates are confounded by entry qualifications and assessment difficulty; g = 0.58 provides a standardised, comparable measure of pedagogical effectiveness.

CONCLUSION

This study designed, implemented, and evaluated an adaptive e-learning platform for physics education at the Federal College of Education, Katsina, Nigeria – a resource-constrained institution typical of many in Sub-Saharan Africa. The findings demonstrate that a mobile-first, accessible, adaptive platform can produce substantial learning improvements while promoting equitable outcomes for students with disabilities.

Physics Achievement Test scores increased significantly from 41.2% (pre-test) to 68.7% (post-test) – an absolute gain of 27.5 percentage points ($t(47)=12.4$, $p<.001$, Cohen's $d=1.42$). The normalised learning gain ($g=0.58$) exceeded the meta-analytic average for simulation-based physics instruction ($g=0.52$). Notably, these gains were achieved despite 87.5% of students using only smartphones and 70.8% experiencing unreliable home internet (<90% uptime). The System Usability Scale score of 80.5 (Grade A, 85th percentile) and module completion rate of 79.5% (far above typical MOOC rates) confirm high usability and engagement.

Critically, this study provides the first empirical evidence from Sub-Saharan Africa that full WCAG 2.1 Level AA compliance can eliminate achievement gaps in e-learning. Students with disabilities ($n=3$) achieved comparable gains ($g=0.56$) to their peers without disabilities ($g=0.58$, $p=0.83$), and no accessibility barriers were reported. Teacher acceptance was strong (perceived usefulness = 4.1/5, behavioural intention = 4.4/5), with the analytics dashboard valued for early identification of at-risk students.

Limitations include the single-group pre-test/post-test design (no causality), small sample (N=48 students, 4 teachers) from one institution, short implementation period (4 weeks), limited statistical power for disability subgroup analyses ($n=3$), absence of a control group, and a researcher-developed test awaiting external validation.

Significance and generalisability – Despite these limitations, the study contributes a replicable, open-source architecture (React/Node.js/PostgreSQL) that other Sub-Saharan African institutions can adapt cost-effectively. It demonstrates that inclusive, adaptive e-learning does not require expensive infrastructure or high bandwidth. For policymakers, it provides evidence to mandate WCAG 2.1 in accreditation standards; for educators, it offers practical guidance on mobile-first design, adaptive sequencing, and simulation-based instruction.

The broader implication is clear: adaptive e-learning can significantly improve physics outcomes while promoting equity across Sub-Saharan Africa, provided that mobile-first design and accessibility standards are prioritised from the outset. The question is no longer whether such platforms work in resource-constrained settings, but how to scale them sustainably. This study provides one replicable model – an open-source, WCAG 2.1-compliant, adaptive platform achieving moderate-to-high learning gains with 87.5% of students using only smartphones. The challenge now lies in implementation, not feasibility.

ACKNOWLEDGMENTS

We would like to extend our deepest gratitude to the Tertiary Education Trust Fund (TETFund) for their invaluable support and funding, which made this project possible.

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