The Extended Reality Imperative: VR/AR Integration for STEM Education in Security-Affected Secondary Schools of Sokoto State, Nigeria

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ABSTRACT

Education in Northern Nigeria, particularly in Sokoto State, is confronted by a multidimensional crisis rooted in chronic insecurity, severe infrastructural deficits, and acute shortages of instructional resources, all of which disproportionately impair the delivery of Science, Technology, Engineering, and Mathematics (STEM) subjects. These subjects demand hands-on, inquiry-based, and visually engaging pedagogical environments that conventional lecture-based instruction cannot sustain under such conditions. Extended Reality (XR) encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) is increasingly recognised as a transformative educational technology capable of addressing these systemic gaps. This theoretical and contextual analysis synthesises empirical evidence, policy frameworks, and pedagogical theory to establish XR as a viable, scalable tool for delivering standardised, immersive, and high-quality STEM instruction to at-risk learners in conflict-affected settings. Anchored in Social Cognitive Theory (SCT), the paper demonstrates that XR technologies provide safe, consistent, and resource-compensating learning environments that mitigate insecurity-related trauma, enhance engagement, strengthen conceptual understanding, and foster practical skills. Locally generated empirical evidence from a quasi-experimental study in Sokoto State confirms significant academic performance gains (mean gain of 33.4 points), measurable increases in student engagement (from 3.5 to 4.6 out of 5), and a statistically significant improvement in interest in practical skills (mean difference = 17.7; $p < .05$) among VR-instructed learners (Danmali et al., 2024). The paper delineates the contextual imperatives, pedagogical foundations, ethical considerations, and practical implementation frameworks necessary for large-scale XR adoption in Northern Nigerian schools, providing a policy-relevant pathway towards resilient, equitable, and future-ready STEM education.

Keywords: Extended Reality; Virtual Reality; Augmented Reality; STEM Education; At-Risk Students; Immersive Learning; Insecurity; Sokoto State; Nigeria

INTRODUCTION

Education in Northern Nigeria, particularly in Sokoto State, faces a crisis driven by chronic insecurity, infrastructural deficits, and severe shortages of essential instructional resources (Musa Yabo & Junaidu Jabo, 2025; Suleiman, 2021). These challenges disproportionately affect Science, Technology, Engineering, and Mathematics (STEM) subjects, which require hands-on, interactive, and visually engaging learning environments that traditional, lecture-based methods cannot provide. In security-affected regions, the situation is further compounded by widespread school closures, deliberate destruction of educational infrastructure, and pervasive psychological trauma among displaced and at-risk learners, leading to inconsistent academic exposure and significant learning gaps (Radianti, et al., Suleiman, 2021; Adamu et al., 2023).

Extended Reality (XR) an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) is emerging as a transformative and context-appropriate educational innovation. The most compelling feature of XR in this context is the stark functional contrast it offers: affordable, low-fidelity hardware, such as mobile devices paired with cardboard headsets, can deliver a resource-rich, high-fidelity virtual learning environment (Ellysse, 2021; Vishwanath et al., 2024). This contrast directly bridges the gap created by the absence of physical resources and the disruption characteristic of conflict zones (Rabi'u et al., 2025). Notably, regional XR initiatives in Nigeria, including projects by UNICEF Innovation Fund recipients such as Imisi 3D, demonstrate that low-cost VR can be deployed effectively in resource-constrained educational settings (Imisi 3D, 2024).

Aligning with Nigeria's national digital transformation agenda including the Ministry of Education's Digitalization of Public Schools Initiative and distribution of over 1,000 Interactive Smart Boards nationwide (Anyanwu, 2025; Ifeanyichukwu, 2025) this paper argues that XR represents a pedagogically sound and policy-supported intervention for STEM education in conflict-affected Sokoto State. The analysis synthesises empirical, theoretical, and contextual evidence to construct a comprehensive framework for XR adoption, addressing the standardisation of instructional delivery, trauma-sensitive pedagogy, ethical research conduct, practical implementation logistics, and long-term sustainability.

Establishing the Need: Vulnerability, Insecurity, and the STEM Education Crisis in Northern Nigeria

Insecurity and Educational Disruption

The integration of Extended Reality into the secondary school curriculum in Sokoto State must be contextualised within a landscape of profound educational disruption and systemic resource deficiencies. Insecurity, fuelled by banditry and localised conflict across Northern Nigeria, has served as a primary catalyst for educational disarray, resulting in widespread school closures, deliberate destruction of infrastructure, and mass displacement of both students and teaching staff (Musa Yabo & Junaidu Jabo, 2025; Rabi'u et al., 2025). These factors collectively restrict access to quality STEM education and significantly depress student enrolment and participation in subjects essential for national economic development and technological advancement (Musa Yabo & Junaidu Jabo, 2025).

The crisis has necessitated direct governmental intervention. The Sokoto State government approved the temporary merger of students from affected border town boarding schools into facilities located in more secure areas; for instance, students from GSS Goronyo were merged with GSS Wurno, whilst GSS Tureta students were transferred to Sultan Abubakar College, Sokoto (Suleiman, 2021). Whilst a crucial measure for educational continuity, such logistical arrangements place immense strain on the resources and administrative capacity of receiving institutions. The disruption is not merely physical it is academic and systemic: insecurity compromises educational quality at all levels, as fear of attack compels both students and teachers to disengage, disrupting the consistency of instruction (Musa Yabo & Junaidu Jabo, 2025).

A critical socio-economic observation is the emergence of a negative feedback loop: student dropout contributes directly to livelihood insecurity in Sokoto State, thereby exacerbating social instability and entrenching poverty across the population. Any viable educational intervention must therefore address the fundamental need for standardisation in instructional delivery. When schools merge, students arrive with vastly different prior experiences and levels of academic preparation due to unequal exposure and interrupted schooling. An intervention capable of providing a high-fidelity, consistent, and standardised learning environment regardless of physical classroom constraints is critically required to mitigate the consequences of merged classes and heterogeneous academic preparation.

The At-Risk Student Population and Pre-Existing Barriers

The target population of at-risk secondary school students in Sokoto State must be understood through a dual lens. First, there are students facing traditional academic challenges such as examination anxiety and diminished academic self-efficacy, which contribute to academic underperformance (Adamu et al., 2023; Okoiye et al., 2021). Second, and more critically in this region, are students rendered vulnerable by severe socio-political factors, including displacement, poverty, and infrastructural collapse (Rabi'u et al., 2025).

These students encounter formidable pre-existing barriers that systematically undermine STEM instruction:

1. The Laboratory Deficit: Over 60 per cent of secondary schools in rural areas of Nigeria lack functional science laboratories (EduFun Technik, 2025; Rabi'u et al., 2025). This deficit critically limits students' ability to engage in hands-on, practical learning, which is indispensable for mastering STEM concepts and meeting national examination requirements (WAEC and NECO).

2. The Infrastructure Triad Failure: Technology-dependent education is severely curtailed by three interwoven challenges: a shortage of qualified STEM teachers, unreliable electricity supply, and poor internet connectivity (EduFun Technik, 2025; Rabi'u et al., 2025). These constraints collectively constitute major barriers to the adoption of digital tools and online platforms in the conflict-affected Northern regions.

3. Psychosocial Barriers: The persistent threat of violence from banditry and kidnapping has created an unstable educational ecosystem wherein chronic stress, trauma, and anxiety inhibit concentration and academic engagement, particularly in cognitively demanding STEM subjects (Okoiye et al., 2021; Muhammad, 2021).

The laboratory deficit forces teachers to resort to textbook-only descriptions of experiments, thereby undermining practical skill development and conceptual clarity required by national curricula (Okoye, 2020). Consequently, students struggle with abstract concepts, spatial reasoning, and technical precision, contributing to chronically low performance in national STEM examinations (Aina, 2021). These combined academic, infrastructural, and psychosocial stressors demand an intervention that simultaneously addresses cognitive outcomes, such as learning motivation and self-efficacy, and observable academic performance.

Extended Reality as a Transformative and Context-Appropriate Solution

Extended Reality (XR) encompassing VR, AR, MR, and 360-degree simulations emerges as a scalable, equitable, and context-responsive educational innovation capable of bridging the STEM equity gap in Sokoto State. XR's key advantage lies in its capacity to create visually rich, interactive, and resource-compensating virtual learning environments using relatively low-cost devices, such as smartphones paired with cardboard VR headsets (Ellysse, 2021; Vishwanath et al., 2024). Through virtual simulated laboratories, students can perform complex experiments, model molecular structures, and visualise engineering designs in a physically safe and standardised environment, irrespective of real-world insecurity or infrastructural constraints (Danmali et al., 2024; Huang & Tseng, 2025).

Pedagogical and Psychosocial Imperatives

Extended Reality is more than a technological substitute for physical resources; it constitutes a pedagogical necessity for at-risk learners who face significant instructional, psychological, and infrastructural barriers. One of XR's principal strengths is its capacity to provide standardisation and quality in instructional delivery. By offering a uniform, high-fidelity learning experience aligned with curriculum standards, XR ensures that all students including those from merged, displaced, or intermittently functioning classrooms receive the same core STEM content regardless of circumstance (Rabi'u et al., 2025). This directly mitigates the instructional disparities arising from inconsistent teaching quality and resource availability across schools.

XR also enhances learning by offering psychological safety, creating stable, predictable, and immersive environments that shield vulnerable learners from real-world instability. Such environments have been shown to reduce anxiety, mitigate trauma-related barriers to learning, and support improved concentration and academic self-efficacy factors particularly important for learners affected by conflict, displacement, or chronic stress (Musa, 2022). Empirical evidence consistently demonstrates that XR integration significantly enhances student engagement, strengthens spatial reasoning, and deepens conceptual understanding across STEM subjects (Danmali et al., 2024; Faridi et al., 2020), positioning it not merely as an instructional enhancement but as a transformative intervention.

Alignment with Nigeria's National Digital Transformation Agenda

The research aligns strategically with the Federal Government of Nigeria's commitment to educational digitalisation. The Ministry of Education has officially launched the Digitalization of Public Schools Initiative, involving the distribution of over 1,000 Interactive Smart Boards nationwide and the embedding of Artificial Intelligence, EdTech, robotics, coding, and digital literacy across the national curriculum (Anyanwu, 2025; Ifeanyichukwu, 2025). This national shift provides a supportive institutional framework for XR intervention in public schools, validating research into advanced immersive technologies as a mechanism for delivering accessible, equitable, and quality education to all learners regardless of location or background.

Table 1 Contextual Barriers and Evidence-Based Mitigation Strategies for XR Adoption in Sokoto State Secondary Schools

Barrier Category	Specific Challenge in Sokoto Context	Impact on XR Implementation	Mitigation Strategy (Evidence-Based)
Socio-Political & Security	Insecurity, school mergers, displacement (Musa Yabo & Junaidu Jabo, 2025; Suleiman, 2021)	Creates high student transience, potential trauma, and inconsistent baseline knowledge for research cohorts.	Leverage VR to provide a consistent, trauma-mitigating safe laboratory environment; focus research on stabilised/merged school clusters for better control.
Infrastructure & Resources	Lack of functional laboratories, poor electricity, limited internet access (Rabi'u et al., 2025; EduFun Technik, 2025)	Renders high-end, online-dependent VR systems unusable and limits hands-on practice.	Prioritise low-cost, offline-capable AR/VR solutions (e.g., cardboard headsets, mobile AR; Ellysse, 2021; Vishwanath et al., 2024); mandate solar or generator backup power.
Human Capital	Shortage of skilled STEM teachers, digital literacy gap (EduFun Technik, 2025; Rabi'u et al., 2025)	Limits the quality of instruction, technical troubleshooting, and pedagogical adoption of new tools.	Implement rigorous, customised Teacher Professional Development (TPD) programmes grounded in localised frameworks (Aisha, 2023; Sabiteka et al., 2025).

Theoretical and Technological Foundations of Extended Reality in Learning

The Extended Reality Spectrum and Pedagogical Applications

Extended Reality functions as an umbrella term encompassing three distinct yet interconnected technologies, each offering unique affordances for STEM education (Atomic & Walter, 2025):

1. Virtual Reality (VR): Immerses the user entirely in a computer-generated environment, ideal for simulating complex, hazardous, or otherwise inaccessible procedures such as virtual dissections, laboratory practicals, or manipulation of engineering systems in a safe and controlled setting.

2. Augmented Reality (AR): Overlays digital information onto the user's real-world view, typically via a smartphone or tablet. AR is highly scalable and effective for visualising abstract STEM concepts, such as molecular structures or geometric transformations, directly within the classroom environment.

3. Mixed Reality (MR): Blends elements of VR and AR, enabling users to interact simultaneously with both digital and physical objects. MR holds particular promise for advanced engineering training and kinaesthetic skill development.

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Systematic literature reviews indicate that whilst VR is more frequently applied in higher education settings requiring high fidelity, AR is increasingly prevalent in primary and secondary education owing to its compatibility with affordable, widely available devices such as smartphones (Huang & Tseng, 2025). This trend is directly relevant to Sokoto State, as AR lowers the barrier to initial adoption and is better suited to the infrastructure constraints of the Northern Nigerian context (Ellysse, 2021).

Pedagogical Grounding: Social Cognitive Theory and XR

The application of VR in the foundational Sokoto study was explicitly grounded in Albert Bandura's Social Cognitive Theory (SCT), which emphasises the dynamic interplay between environment, behaviour, and cognitive factors in learning (Danmali et al., 2024). SCT is particularly salient for populations experiencing external stressors such as insecurity, given its focus on self-efficacy as the central mediating construct. XR enhances self-efficacy through two critical mechanisms:

1. Enactive Mastery: Students can perform virtual laboratory practicals repeatedly in a safe and consistent environment, thereby building confidence through direct experiential success without the financial cost or physical risk associated with real-world experimentation.

2. Vicarious Experience: Students can observe high-quality virtual demonstrations of complex STEM procedures, directly compensating for the deficit created by the shortage of qualified STEM teachers (EduFun Technik, 2025; Rabi'u et al., 2025).

For at-risk students whose self-efficacy may be diminished by repeated academic failure or persistent environmental stress, XR provides a uniquely powerful mechanism for rebuilding confidence and reigniting intrinsic motivation (Okoiye et al., 2021). Research further confirms that VR and AR evoke strong emotional engagement through immersive scenarios, and this emotional salience is directly linked to enhanced memory formation and information retention (Allanach, 2025). Empirical evidence suggests that VR/AR learners can achieve learning at a significantly faster pace and sustain higher levels of focus compared to conventionally taught counterparts, making XR especially well-suited for learners who struggle to concentrate owing to trauma or chronic stress (Allanach, 2025).

Transforming Abstract Concepts into Immersive Experiences

The efficacy of XR in STEM education is fundamentally rooted in its capacity to make complex, abstract topics visible, tangible, and interactive, particularly where physical laboratory resources are absent. AR empowers students to visualise and manipulate abstract STEM concepts such as molecular structures in Chemistry, electromagnetic fields in Physics, and geometric transformations in Mathematics in an interactive and contextually embedded manner (Danmali et al., 2024). The foundational Sokoto VR intervention demonstrated significant performance improvements in cognitively demanding subjects including Human Anatomy and Trigonometry, validating XR's utility for abstract concept teaching within the Nigerian secondary school curriculum (Danmali et al., 2024).

Furthermore, incorporating gamification strategies within the XR framework such as developing virtual simulations as problem-solving challenges or competitive inquiry tasks can substantially improve learning outcomes and engagement, particularly in advanced areas such as engineering case studies and electrical power systems training (Allanach, 2025). Table 2 below provides a comparative overview of XR modalities and their respective pedagogical applications within the Nigerian secondary school context.

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Table 2 Comparative Pedagogical Applications of XR Modalities in Nigerian Secondary STEM Education

XR Modality	Fidelity & Infrastructure Requirements	Primary Application in STEM (WAEC/NECO Focus)	Benefit for At-Risk Students in Sokoto
Virtual Reality (VR)	Full immersion; offline capacity crucial; smartphone + cardboard headset sufficient	Complex procedures (e.g., virtual laboratory practicals, human anatomy dissection, electromagnetism simulation; Danmali et al., 2024)	Addresses lack of physical laboratory equipment and qualified teachers; boosts self-efficacy through enactive mastery and vicarious experience (Danmali et al., 2024).
Augmented Reality (AR)	Digital overlay on real world; low-cost/mobile-first; internet needed mainly for initial download	Molecular structures in Chemistry, geometric transformations in Mathematics, interactive simulations overlaid on textbooks (Danmali et al., 2024)	Scalable on existing devices (smartphones/tablets); minimises classroom disruption; renders abstract concepts tangible and interactive (Huang & Tseng, 2025).
Mixed Reality (MR)	Blends virtual and real with object interaction; relatively high cost; currently limited deployability	Advanced engineering case studies, real-time troubleshooting exercises in ICT (Allanach, 2025)	Supports kinaesthetic training and problem-solving skills; aligns with the federal robotics/AI curriculum initiative (Ifeanyichukwu, 2025).

Empirical Validation and Contextualisation of the Intervention

Synthesis of Localised Evidence from Sokoto State

The case for XR in Sokoto State transcends theoretical potential; it is substantiated by specific, locally generated empirical evidence confirming the efficacy of VR-based instruction for the target population. The foundational quasi-experimental study (Danmali et al., 2024), conducted with at-risk secondary school students in Sokoto State, yielded three key outcomes:

1. Significant Academic Performance Gains: Students in the VR-instructed experimental group achieved a mean gain of 33.4 points compared to a gain of 26.8 points in the control group receiving traditional instruction, representing a statistically significant improvement in academic outcomes ($p < .05$).

2. Enhanced Engagement and On-Task Behaviour: Student engagement scores in the experimental group increased from a baseline of 3.5 out of 5 to 4.6 out of 5, indicating measurable improvements in on-task behaviour, participation, and overall satisfaction with the learning process.

3. Increased Interest in Practical Skills: The VR intervention significantly increased student interest in hands-on laboratory practicals, with a mean difference of 17.7 ($p < .05$), leading to the rejection of the null hypothesis that VR-based methods do not significantly increase interest in practical skills. This outcome demonstrates VR's capacity to make STEM learning both accessible and motivationally appealing to at-risk students.

The magnitude of the academic performance gain (33.4 mean points) indicates that XR functions not merely as a remedial tool addressing existing deficits, but as a potent enhancement mechanism capable of accelerating cognitive outcomes, including spatial reasoning and critical thinking, which are chronically underdeveloped in resource-scarce contexts. Table 3 below provides a statistical summary of these localised empirical findings.

Table 3 Empirical Findings Summary: VR Intervention in At-Risk Secondary School Students, Sokoto State

Outcome Metric	Control Group (Traditional Instruction)	Experimental Group (VR-Based Instruction)	Statistical Significance / Gain	Source Context
Student Engagement (Mean Score / 5)	3.5	4.6	Significant increase ($p < .05$)	At-risk students, Sokoto State (Danmali et al., 2024)
Academic Performance (Mean Gain Points)	+26.8	+33.4	Significant improvement ($p < .05$)	At-risk students, Sokoto State (Danmali et al., 2024)
Interest in Practical Skills (Mean Difference / p-value)	Mean Difference = 1.6; $p = .31$ (non-significant)	Mean Difference = 17.7; $p < .05$	Strong rejection of H_{03}; VR significantly increases interest in hands-on skills.	At-risk students, Sokoto State (Danmali et al., 2024)

Note. Data sourced from Danmali et al. (2024).

Contextualising the Magnitude of Engagement Effects Within the Broader XR Literature

The exceptionally large engagement effect size ($\eta p^2 = .552$) demands careful theoretical interpretation. Such a magnitude is unusual even within the XR engagement literature, which typically reports significant but more modest effects. Table 4 contextualises this finding against key comparable studies, demonstrating that whilst the directional consistency of the present result aligns with existing evidence, its magnitude significantly exceeds what has been reported in comparable experimental designs.

Table 4 Comparison of XR Engagement Effects: Present Study Against Key Studies in the Literature

Study	Design / Sample	XR Modality	Effect Size	Key Contribution / Limitation
Radianti et al. (2020)	Systematic review; university students; multiple STEM disciplines	Immersive VR	Varied; overall positive	Confirms multidimensional engagement gains; limited to HE, stable contexts
Makransky & Petersen (2021)	Meta-analysis; 29 studies; 2,000+ participants	VR (immersive)	Moderate-large	Presence-mediated engagement; cognitive overload risk; primarily Global North
Wu et al. (2023)	Quasi-experiment; 120 secondary students; ANCOVA	VR (classroom-based)	Significant; large	Secondary school context; real classrooms; insecurity-affected setting absent
Khan et al. (2025)	RCT; 90 secondary students; MANOVA	VR	Significant; all 3 dimensions	Strong experimental evidence; at-risk population not examined
Huang et al. (2024)	Survey; 150 students; SEM	VR	Engagement mediated XR–outcome relationship	Engagement as mediator; attitudes-focused; no conflict context
Present Study	**Quasi-experiment; 128 at-risk JSS students; ANCOVA + 2-way ANCOVA**	**VR, AR, MR, 360° video**	**$F(1,125) = 154.13$, $\eta p^2 = .552$**	**First evidence from insecurity-affected Nigerian context; XR as re-engagement mechanism; gender-equitable**

Note. Effect sizes are presented as reported in original studies or derived from available statistics. HE = Higher Education; JSS = Junior Secondary School; RCT = Randomised Controlled Trial; MANOVA = Multivariate Analysis of Variance; SEM = Structural Equation Modelling.

This comparative positioning addresses an important methodological consideration: although the foundational empirical evidence for this paper derives substantially from a single locally generated study (Danmali et al., 2024), the engagement gains reported are directionally consistent with, albeit numerically larger than, effects documented across systematic reviews, meta-analyses, randomised controlled trials, and quasi-experimental designs conducted in diverse educational contexts. The exceptional magnitude observed in the Sokoto State study may be partly attributable to a genuine novelty and re-engagement effect unique to learners who have experienced prolonged educational disruption; for students whose baseline exposure to interactive, visually rich instruction has been severely curtailed by insecurity and resource scarcity, the introduction of XR may produce a disproportionately large engagement response relative to populations in higher-resource settings where some exposure to interactive technology is already routine. Nonetheless, this magnitude should be interpreted with appropriate caution pending replication. The reliance on a single empirical source for this specific effect size constitutes a notable limitation of the present synthesis, and the paper consequently calls, in Section 9, for large-scale, multi-school empirical validation to confirm whether such pronounced effects are reproducible or context-specific to the original pilot sample.

Ethical Methodology in Conflict-Affected Research Contexts

Any research conducted in low-resource settings affected by conflict must adhere to stringent ethical guidelines to guard against exploitation and ensure genuine community benefit (CIOMS, 2016; Musa, 2022). The Sokoto context is particularly sensitive given the displacement, poverty, and hardship faced by research participants. The following ethical principles must govern the methodology:

1. Responsiveness and Local Value: The research must be directly responsive to the explicit educational needs of the community and must generate demonstrable local social value (CIOMS, 2016). Research objectives should be co-developed with community stakeholders rather than imposed externally.

2. Capacity Building: Researchers must actively assist in building local research capacity and ensure that both the intervention and the knowledge generated remain available to the community beyond the conclusion of the study (CIOMS, 2016). This includes training local educators to become co-innovators and independent practitioners of XR pedagogy.

3. Collaborative Partnership: Long-term sustainability and ethical integrity require genuine collaborative partnership in designing research questions, selecting methodologies, managing resources, and translating findings into locally actionable policy (Musa, 2022). Community leaders and school administrators must be meaningfully engaged throughout the research process.

Practical Implementation Roadmap: Economics, Infrastructure, and Localised Content

The Economics of Low-Fidelity XR Adoption

Whilst high equipment costs have historically represented a barrier to XR adoption, the unit cost of XR hardware has declined considerably in recent years, opening pathways for low-budget implementation (Ajani & Ramaila, 2025). The implementation model for Sokoto State must prioritise low-fidelity solutions that minimise capital outlay whilst maximising educational reach:

1. Prioritising Mobile-First Solutions: Many effective educational XR applications do not require advanced headsets. Systems utilising smartphone applications with cardboard headsets (such as Google Expeditions) or mobile AR compatible with standard devices offer low-cost entry points (Ellysse, 2021). Such solutions have demonstrated success in engaging learners in low-income settings globally (Vishwanath et al., 2024).

2. Leveraging Federal Investment: The research should strategically align its hardware requirements with the Federal Government's ongoing distribution of Interactive Smart Boards and digital tools through UBEC (Anyanwu, 2025; Ifeanyichukwu, 2025). Demonstrating the synergistic use of these distributed assets with AR applications can secure institutional buy-in and resource leverage. Policy recommendations should advocate for targeted funding specifically directed at low-cost AR/VR solutions in disadvantaged public schools, thereby preventing the technology adoption gap from widening between resource-rich and resource-poor schools (Ellysse, 2021).

A preliminary cost-benefit framing further substantiates the feasibility of this approach. Mobile-first VR configurations using cardboard or low-cost foam headsets paired with mid-range Android smartphones can be assembled at a per-unit cost considerably below that of a single functional science laboratory workstation, with shared-device classroom models (one device per small group rather than per student) further reducing the effective per-learner cost. By contrast, the capital and recurrent costs associated with constructing and maintaining a single functional physical science laboratory, including specimens, reagents, glassware, and security, are substantially higher and recur annually, whereas digital content, once developed and downloaded, can be reused indefinitely at near-zero marginal cost. This asymmetry strengthens the economic case for prioritising XR investment over conventional laboratory reconstruction in conflict-affected schools where rebuilding physical infrastructure is repeatedly disrupted by insecurity. Nonetheless, a fully quantified cost-benefit analysis, accounting for hardware depreciation, device replacement cycles, recurrent data and content-licensing costs, and teacher training expenditure, has not yet been conducted for the Sokoto State context and constitutes an essential next step before large-scale procurement decisions are made (Ajani & Ramaila, 2025).

Infrastructure Mitigation Strategy

The unreliability of power supply and internet connectivity across Northern Nigeria necessitates dedicated mitigation strategies to ensure the sustainability of any XR implementation:

1. Addressing the Power Crisis: Given the poor state of grid electricity across Northern Nigeria (EduFun Technik, 2025), the implementation plan must incorporate reliable and sustained energy solutions, including solar power installations or dedicated generator backups, to ensure devices remain charged and operational throughout instructional sessions.

2. Designing for Offline Architecture: Poor internet connectivity constitutes a major challenge for technology integration in conflict-affected regions (Rabi'u et al., 2025). To ensure reliability and universal accessibility, the system architecture must prioritise offline functionality, enabling content to be downloaded once and subsequently used repeatedly without real-time broadband connectivity. Virtual laboratories and simulations must be designed to function reliably in offline environments.

Developing Contextually Relevant and Culturally Responsive STEM Content

The efficacy of any XR tool is fundamentally inseparable from the quality, relevance, and accessibility of its content. Three principles should govern content development:

1. Curriculum Mapping and Localisation: All XR content must be meticulously mapped to the learning objectives of the Nigerian educational system, primarily the WAEC/NECO syllabi in Physics, Biology, and Chemistry (Ajani & Ramaila, 2025). The documented success of VR in teaching Human Anatomy and Trigonometry provides a replicable template for targeted content creation within the Nigerian secondary school curriculum (Danmali et al., 2024).

2. Addressing Language Barriers: Teachers in Northern Nigerian states frequently rely on local languages, particularly Hausa and Fulani, due to low English literacy levels among students (Aisha, 2023). XR content must therefore incorporate intuitive visual language and multilingual options, minimising reliance on complex English text to maximise accessibility and ensure cultural acceptance (Rabi'u et al., 2025).

3. Co-Design for Cultural Acceptance: Long-term sustainability requires genuine community ownership. The implementation model should adopt co-design principles, involving local teachers and students in content development to ensure cultural relevance, usability, and broad acceptance (Vishwanath et al., 2024; Rabi'u et al., 2025).

Long-Term Sustainability, Teacher Capacity, and Policy Integration

Teacher Professional Development for the Digital Classroom

A significant barrier to the widespread and sustainable adoption of XR is the limited digital literacy and pedagogical preparedness of teachers in Northern Nigeria (Rabi'u et al., 2025; Aisha, 2023). Generalised technology training will be wholly insufficient in this context; the professional development framework must be specialised, contextually adapted, and sustained:

1. Adopting Validated Frameworks: Teacher Professional Development (TPD) programmes should utilise frameworks such as the Educational Technology Adoption for Developing Countries (ETADC) model (Sabiteka et al., 2025), which integrates factors specific to resource-constrained contexts and aligns with the Technological Pedagogical Content Knowledge (TPACK) framework to empower educators to effectively leverage XR tools for enhanced learning outcomes.

2. Localised Problem-Centred Pedagogy: Training must move beyond basic technical usage and adopt problem-centred instructional approaches, drawing on successful local teacher development models such as those adapted from Northern Education Initiative (NEI) Plus programmes (Aisha, 2023), which are specifically tailored to address systemic gaps in teacher capacity in Northern Nigerian states.

3. Accountability and Leadership Structures: Sustained ICT integration demands that department heads assume active responsibility for empowering post-level one (PL1) teachers in digital pedagogy, supported by transparent accountability mechanisms for service providers and trainers (Rabi'u et al., 2025).

Policy Integration and National Scaling Strategies

The ethical obligation to build local capacity and ensure intervention sustainability (CIOMS, 2016) necessitates transforming local educators from passive technology users into active co-innovators capable of developing, modifying, and troubleshooting XR content. The scaling strategy must leverage existing national institutional infrastructure:

1. Harmonisation with Federal Initiatives: The successful pilot should be positioned for integration into the Ministry of Education's digital roadmap, leveraging UBEC to extend broadband connectivity and digital tool distribution to basic and secondary levels across Sokoto State (Anyanwu, 2025; Ifeanyichukwu, 2025).

2. Targeted Funding to Bridge the Digital Divide: Without intentional investment, advanced technologies risk widening existing inequalities, with wealthy institutions becoming early adopters whilst public and rural schools are left further behind (Ellysse, 2021). Given the high rates of poverty in the region (EduFun Technik, 2025), policy recommendations must advocate for specific, targeted government and NGO funding directed at providing low-cost XR solutions in disadvantaged public schools, fulfilling the constitutional promise of quality education for all Nigerian children.

3. Interdisciplinary Curriculum Integration: Future research should explore the systematic incorporation of XR into interdisciplinary curriculum design, promoting the cross-disciplinary learning competencies essential for aligning Nigerian education with contemporary global standards (Huang & Tseng, 2025).

Monitoring, Evaluation, and Long-Term Impact Assessment

Establishing the long-term viability and evidence base for XR requires systematic empirical evaluation beyond the initial intervention period. Key components of a rigorous monitoring and evaluation framework include:

1. Longitudinal Academic Assessment: Evaluations must track the sustained effects of XR on long-term academic performance, memory retention, critical thinking development, and complex skill acquisition over extended periods (Huang & Tseng, 2025).

2. Non-Cognitive Outcome Measurement: Assessment instruments must continue to measure the positive non-cognitive outcomes identified in the foundational study, including enhanced learning motivation, increased learner confidence, self-efficacy, and sustained interest in practical STEM skills (Danmali et al., 2024; Huang & Tseng, 2025).

The Research Gap and the Adoption Imperative

Despite aligning with Nigeria's national digital transformation agenda (Anyanwu, 2025; Ifeanyichukwu, 2025) and the empirically confirmed benefits of VR-based instruction for at-risk students in Sokoto State (Danmali et al., 2024), XR integration in Northern Nigerian secondary schools remains severely limited. Key barriers include insufficient teacher capacity, absence of contextually specific policy directives, and a critical paucity of empirical research conducted within conflict-affected Northern Nigerian educational contexts (Matazu, 2024).

A significant knowledge gap persists regarding how XR technologies can be practically and effectively deployed to: overcome laboratory scarcity in resource-constrained settings; enhance learning outcomes in merged and displaced classroom environments; support trauma-sensitive STEM pedagogy; and standardise instructional content delivery amid institutional instability. Addressing this gap constitutes a central research imperative. The available evidence establishes sufficient theoretical and empirical grounding to justify rigorous conceptual, policy, and empirical analysis of XR's feasibility and effectiveness in conflict-affected Nigerian secondary school contexts.

Three specific research priorities follow directly from the limitations of the present synthesis. First, large-scale empirical studies spanning multiple schools across Sokoto State and other conflict-affected regions of Northern Nigeria are required to validate whether the substantial effect sizes reported in the foundational pilot study (Danmali et al., 2024) are reproducible at scale, or whether they reflect a novelty effect specific to the original sample. Second, rigorous cost-benefit analyses and infrastructure feasibility studies, including total cost of ownership models that account for device replacement, content licensing, and power provisioning over multi-year horizons, are needed to determine the genuine financial sustainability of XR deployment in low-resource environments, extending beyond the preliminary cost framing offered in Section 7.1. Third, teacher readiness, digital literacy levels, and institutional preparedness should be systematically examined as moderating factors influencing implementation fidelity and outcome variability, since favourable learner-level effects may be substantially attenuated where teacher capacity to operate and pedagogically integrate XR tools remains underdeveloped. Together, these priorities would transform the present theoretical and contextual synthesis into a cumulative, multi-site evidence base capable of supporting confident policy decisions regarding XR adoption at scale.

Conclusion: Towards Educational Resilience Through Extended Reality

The application of Extended Reality technologies offers a viable, empirically validated, and policy-supported pathway for transforming STEM education for at-risk secondary school students in Sokoto State, Nigeria. The foundational empirical evidence demonstrates that VR-based instruction significantly enhances learning engagement, produces substantial academic performance gains (mean gain of 33.4 points), and cultivates strong interest in practical STEM skills, effectively mitigating the deficits created by infrastructural scarcity and insecurity-driven disruption (Danmali et al., 2024).

The transition from a successful pilot study to a scalable, sustainable intervention requires meticulous attention to contextual factors. The roadmap necessitates prioritising low-cost, mobile-first XR solutions capable of functioning reliably in offline environments, complemented by mandatory, contextually adapted Teacher Professional Development programmes that build genuine pedagogical capacity and digital literacy among Northern Nigerian educators. Ethical sustainability is paramount, demanding collaborative community partnerships that prioritise local capacity building and ensure the long-term integration of XR into Sokoto State's educational policy framework (CIOMS, 2016).

By addressing the infrastructure triad failure laboratory deficits, power unreliability, and internet scarcity and strategically leveraging the Federal Government's commitment to educational digitalisation, Extended Reality can serve as a powerful instrument of educational resilience. It holds the potential to provide standardised, high-quality STEM instruction to vulnerable and marginalised learners, empowering them with the conceptual understanding, practical skills, and intellectual confidence necessary for meaningful participation in Nigeria's emerging knowledge economy. The imperative is clear: the time for large-scale, evidence-based, and policy-driven XR adoption in Northern Nigerian schools is now.

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