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ENHANCING STEM EDUCATION THROUGH VIRTUAL REALITY AND AUGMENTED REALITY: IMPLICATIONS FOR LEARNING OUTCOMES AND ECONOMIC DEVELOPMENT IN NIGERIA

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Abstract

This study investigated the integration of Virtual Reality (VR) and Augmented Reality (AR) technologies into STEM education within the Nigerian secondary and tertiary educational contexts, drawing on a systematic synthesis of global and domestic empirical literature, grounded in Constructivist Learning Theory, the Diffusion of Innovations Theory, and the Technology Acceptance Model (TAM). A conceptual-analytical framework was developed that incorporates cost-benefit analysis (CBA) to evaluate the economic implications of technology-enhanced STEM education. Findings indicate that VR- and AR-

enhanced STEM instruction yields measurable improvements in student engagement, knowledge retention (up to 40% over traditional methods), productivity, and the development of critical twenty-first-century competencies, including problem-solving, computational thinking, and collaborative skills. The study recommended a contextually adapted implementation framework for Nigerian educational institutions and offered concrete policy recommendations for government agencies, school administrators, and international development partners.

Keywords: Virtual Reality, Augmented Reality, STEM Education, Learning Outcomes, Economic Development.

Introduction

Science, Technology, Engineering, and Mathematics (STEM) education has emerged as the principal driver of knowledge economies in the twenty-first century. The capacity of a nation to generate sustained innovation,

compete in global markets, and address complex socioeconomic challenges is increasingly tied to the quality and accessibility of its STEM educational infrastructure (Xie et al., 2015). The Fourth Industrial Revolution, characterised by the

convergence of digital, biological, and physical technologies, has further amplified the urgency of equipping learners with robust STEM competencies that extend well beyond rote memorisation to encompass critical thinking, computational reasoning, creative problem-solving, and adaptive collaboration (Schwab, 2016).

Against this backdrop, Virtual Reality (VR) and Augmented Reality (AR) have attracted considerable scholarly and institutional attention as transformative pedagogical tools. Unlike conventional instruction, which often constrains learners to passive reception of abstract information, VR and AR technologies generate immersive, interactive, and experiential learning environments in which students engage dynamically with scientific concepts, engineering simulations, mathematical visualisations, and technological systems (Radianti et al., 2020). The empirical record from developed economies, particularly the United States, South Korea, China, and several European nations demonstrates consistently that VR/AR-enhanced STEM instruction improves engagement, deepens conceptual understanding, and accelerates the acquisition of practical skills (Chen et al., 2019; Merchant et al., 2014).

In Nigeria, however, STEM education confronts a formidable convergence of

structural, infrastructural, and pedagogical challenges. With a population exceeding 220 million, Nigeria has one of the largest youth populations in the world; yet its educational system has struggled to translate that demographic potential into economic productivity. Secondary schools across the country continue to rely on chalk-and-talk pedagogies, while laboratories are frequently non-functional or poorly equipped (Okafor et al., 2022). Student performance in high-stakes STEM examinations administered by the West African Examinations Council (WAEC) and the National Examinations Council (NECO) has remained persistently low, with national averages in mathematics and the sciences repeatedly falling below 50% over the past decade (Adeyemo, 2022). The consequences of these deficits manifest as a growing skills gap that constrains industrial capacity, technological innovation, and the economic diversification objectives central to Nigeria's Vision 2030 and successive national development plans. Despite the well-documented transformative potential of immersive technologies in educational contexts, their adoption within Nigerian schools and universities remains nascent, largely anecdotal, and insufficiently theorised. While several institutions operate e-learning centres and have incrementally incorporated

digital tools into their instructional practices, the systematic integration of VR and AR specifically into STEM curricula and the rigorous evaluation of the resulting learning and economic outcomes have not received the scholarly attention they merit (Enyiazu, 2021; Olumide et al., 2021). This study, therefore, addresses this critical research gap through a comprehensive, theoretically grounded, and analytically rigorous examination of the integration of VR and AR into STEM education in Nigeria and aims to answer these research questions:

1. What is the baseline level of STEM academic performance, science motivation, and student engagement among secondary school students in the study area?
2. What are the determinants of VR and AR technology adoption among students?
3. What is the economic viability of integrating VR and AR into STEM education in Nigeria?

Literature Review

Virtual Reality (VR) refers to a computer-generated, three-dimensional environment that users can inhabit and interact with through dedicated hardware such as head-mounted displays (HMDs), motion controllers, and haptic feedback devices, in ways that replicate

or depart from real-world sensory experience (Burdea & Coiffet, 2003). The defining characteristic of VR is its capacity to induce a sense of presence, a psychological state in which the user perceives the virtual environment as genuinely real, facilitating deep cognitive engagement with simulated phenomena (Riva et al., 2019). In educational settings, VR enables learners to conduct virtual dissections, explore subatomic particles, traverse the solar system, or experience historical events without the logistical, financial or safety constraints of real-world laboratories and fieldwork.

Augmented Reality (AR), by contrast, superimposes digitally generated content including three-dimensional models, textual annotations, animations, and interactive overlays onto the physical world as perceived through a smartphone camera, tablet, or AR-specific headset (Craig, 2013). Unlike VR, which entirely supplants reality, AR enriches it, allowing learners to manipulate digital representations of STEM concepts while remaining grounded in their physical environment. This characteristic makes AR particularly well-suited to collaborative, inquiry-based pedagogies in conventional classroom settings (Akçayır & Akçayır, 2017). STEM education, as conceptualized in this study, encompasses the integrated teaching and

learning of Science, Technology, Engineering, and Mathematics disciplines, with emphasis on cross-disciplinary problem-solving, practical application, and the cultivation of competencies relevant to the contemporary economy. The integration of VR and AR into STEM instruction thus represents the intersection of immersive technology and integrated disciplinary pedagogy, a domain of rapidly expanding scholarly and practical significance.

The global literature on VR and AR in STEM education reflects a broad and growing consensus around their pedagogical effectiveness. Radianti et al. (2020) conducted a systematic review of 38 peer-reviewed studies on immersive VR applications in higher education, finding consistent evidence of enhanced student engagement, deeper conceptual understanding, and improved skill acquisition, particularly in medicine, science, and engineering disciplines. Similarly, Merchant et al. (2014) performed a meta-analysis of 69 empirical studies on game-based virtual simulations, reporting an overall mean effect size of $d = 0.51$, indicating a moderate-to-strong positive impact on learning outcomes.

In the domain of science education specifically, Parong and Mayer (2018) compared VR-based and slide-based

instruction on scientific concepts and found that, while VR enhanced engagement, its cognitive benefits were maximised when combined with structured instructional scaffolding. This finding underscores an important nuance: VR and AR are not pedagogically self-sufficient; their effectiveness is contingent on the quality of pedagogical design surrounding their deployment. Chen et al. (2019) extended this insight in a study of AR-enhanced chemistry instruction in Taiwanese secondary schools, demonstrating that AR-integrated lessons produced significantly higher post-test scores and science self-efficacy compared to control groups, but only when accompanied by teacher facilitation and student collaboration protocols. In the mathematics domain, Hwang and Hu (2013) demonstrated that AR-based geometry instruction improved spatial reasoning and problem-solving performance among middle school students, with particular benefits observed for learners with weaker initial spatial ability. Likewise, Lin et al. (2021) reported that university engineering students who completed VR-based structural mechanics simulations achieved significantly higher scores on application-level examination items than those who received traditional instruction, suggesting that VR is particularly effective at

bridging the gap between theoretical knowledge and practical application.

Research has also examined the affective dimensions of VR and AR-enhanced STEM learning. Makransky et al. (2019) found that VR-based laboratory simulations in biology increased students' situational interest and motivation, with these affective gains mediating subsequent knowledge retention. Importantly, the study also identified the risk of cognitive overload in highly immersive VR environments, cautioning against the uncritical assumption that greater immersion invariably produces better learning outcomes. This finding aligns with Mayer's Cognitive Theory of Multimedia Learning, which posits that learning is optimised when cognitive load is carefully managed (Mayer, 2009).

STEM education in Nigeria is beset by a complex web of interrelated challenges that collectively undermine student performance and limit the country's human capital development agenda. At the infrastructural level, the majority of Nigeria's secondary schools lack functional science laboratories, with estimates suggesting that fewer than 30% of public secondary schools have laboratory equipment that meets minimum standards (Okafor et al., 2022). This infrastructural deficit fundamentally compromises the quality of practical STEM instruction, as students are

denied the hands-on experimental experiences that are essential to the development of scientific reasoning and technical competencies.

Pedagogically, STEM instruction in Nigeria continues to be dominated by teacher-centred, examination-focused approaches that prioritise memorisation over understanding. This orientation is partly a product of the high-stakes examination system, which incentivises surface-learning strategies and discourages the exploratory, inquiry-based pedagogies that are associated with deeper STEM competency development (Adeyemo, 2022). Teacher quality and professional development represent additional critical constraints; a substantial proportion of STEM teachers in Nigerian secondary schools, particularly in rural and semi-urban areas are either unqualified or underqualified and access to continuing professional education is severely limited (Abonyi & Umeh, 2014).

The consequences of these deficits are reflected in persistent and troubling patterns of student underperformance. National analyses of WAEC and NECO results consistently reveal that fewer than 50% of candidates achieve credit passes in mathematics and core science subjects in any given examination cycle, a pattern that has shown little meaningful improvement over the past decade

(Adeyemo, 2022). This underperformance translates directly into a limited number of graduates capable of meeting the demands of Nigeria's emerging technology, manufacturing, and services sectors, with cascading consequences for economic diversification and growth.

Beyond these structural challenges, STEM education in Nigeria is also constrained by gender inequalities, geographic disparities in resource distribution, and the limited integration of indigenous knowledge systems into science curricula factors that further restrict access to quality STEM education for significant segments of the population (Olumide et al., 2021). The digital divide compounds these inequities: while urban centres such as Lagos, Abuja, and Kano have experienced significant improvements in internet connectivity and device availability over the past five years, rural educational institutions remain largely disconnected from the digital resources and tools that are increasingly central to contemporary STEM pedagogy.

The adoption of VR and AR in educational systems of developing economies, including Nigeria, faces a distinctive set of barriers that differ in character and intensity from those encountered in high-income country contexts. Hardware cost represents the most immediate

constraint: entry-level VR headsets remain financially inaccessible for most Nigerian public schools, and the total cost of ownership encompassing hardware, software licensing, maintenance, and technical support poses a formidable barrier to institutional adoption (Oyelaran & Adeyemi, 2021).

Infrastructure-related constraints compound the hardware cost barrier. Reliable electricity supply, high-speed internet connectivity, and adequate physical space are preconditions for effective VR and AR deployment that many Nigerian schools cannot dependably provide. Load-shedding and power outages which affect up to 70% of Nigerian households and institutions for significant portions of each day can disrupt immersive learning sessions and damage sensitive hardware, reducing the cost-effectiveness of technology investments (Enyiazu, 2021).

Despite these barriers, there are significant and growing enablers of VR and AR adoption in the Nigerian educational context. The proliferation of affordable smartphones, Nigeria's smartphone penetration rate exceeded 45% in 2023 and continues to rise creates a viable platform for AR delivery through mobile applications, circumventing the need for expensive dedicated hardware (Statista, 2024). The rapid expansion of 4G network coverage by major

telecommunications providers, combined with government initiatives such as the National Broadband Plan 2020–2025, is progressively extending internet access to secondary and tertiary institutions in previously underserved areas (Nigerian Communications Commission, 2023).

The emergence of open-source and low-cost VR and AR development platforms including Unity, Unreal Engine, and Google's ARCore has also democratised content creation, enabling local developers, educators, and researchers to produce culturally relevant and contextually appropriate educational content without the prohibitive costs associated with proprietary commercial solutions (Oyelaran & Adeyemi, 2021). Several Nigerian universities and private technology firms have begun piloting indigenous VR and AR educational applications, suggesting that local capacity for technology-enhanced pedagogy is nascent but growing (Enyiazu, 2021).

The economic rationale for investing in VR- and AR-enhanced STEM education spans multiple analytical dimensions. At the microeconomic level, improved STEM learning outcomes translate into enhanced individual human capital, which is associated with higher labour market productivity, greater earnings potential, and increased occupational mobility (Hanushek & Woessmann, 2015). At

the macroeconomic level, the aggregate improvement in STEM graduate quality and quantity drives innovation, technological adoption and total factor productivity, the primary engines of sustained economic growth in knowledge economies (Kendall, 2023).

For Nigeria specifically, the economic stakes are considerable. The Federal Government's economic diversification agenda, articulated through successive medium-term national development plans identifies STEM-intensive sectors, including information technology, manufacturing, renewable energy, and agri-technology, as the principal vectors of non-oil growth. The realisation of this agenda is contingent on the availability of a STEM-capable workforce of sufficient scale and quality, a prerequisite that the current educational system demonstrably fails to meet (Okafor et al., 2022).

International evidence supports the strong economic returns to STEM education quality. Hanushek and Woessmann (2015) in a seminal cross-national analysis, demonstrated that a one standard deviation improvement in student cognitive test scores, equivalent to the kind of learning gains associated with high-quality educational interventions is associated with approximately a 2% increase in annual GDP growth. Applied to Nigeria's context, even modest improvements in STEM learning

outcomes, scaled across the country's large student population, could generate economically transformative dividends over a 10–20-year horizon.

Research Methodology

This study is primarily in nature with data collection, framework development and economic analysis. The primary study population comprised secondary school students (specifically in Years 10 and 11, corresponding to Senior Secondary School classes SSS1 and SSS2), STEM teachers, and school administrators in selected public and private secondary schools across three Nigerian states: Lagos (South-West), Kano (North-West), and Enugu (South-East). This multi-state, geographically distributed sampling strategy was designed to ensure that regional diversity in socioeconomic context, infrastructure endowments, and cultural orientations toward technology is adequately represented in the study.

A purposive sampling approach was used to select schools that meet minimum criteria for technology infrastructure (at a minimum, access to a functional computer laboratory with internet connectivity), ensuring the feasibility of VR and AR technology deployment. Within selected schools, stratified random sampling was used to select participants, stratifying by

gender, academic stream (science vs. non-science) and prior technology exposure. A total sample of 480 students (160 per state divided equally between experimental and control groups), 60 teachers and 30 administrators was targeted, providing adequate statistical power for the primary quantitative analyses.

Quantitative data was collected through validated pre- and post-intervention academic assessments in biology, chemistry, physics, and mathematics, aligned with the Nigerian National Curriculum; the Science Motivation Questionnaire II (SMQ-II; Glynn et al., 2011), adapted for the Nigerian context, to measure student engagement, motivation; and a technology acceptance instrument based on the TAM, measuring perceived usefulness and perceived ease of use of VR and AR tools. Qualitative data are gathered through semi-structured focus group discussions with students (six groups of six to eight participants) and in-depth interviews with teachers and administrators. Interview and focus group protocols were developed to explore participants' experiences with VR/AR learning, perceived challenges and enablers of adoption and contextual factors mediating technology effectiveness.

Pre- and post-intervention test scores are compared between experimental and control

groups using independent samples t-tests and analysis of covariance (ANCOVA), controlling for baseline performance, gender, and school type. Effect sizes are calculated using Cohen's test to assess the practical significance of observed differences. Engagement and motivation data from the SMQ-II are analysed using descriptive statistics and regression analysis to examine predictors of technology-related motivation. Qualitative data are analysed using thematic

analysis following the six-phase framework proposed by Braun and Clarke (2006), with themes coded independently by two researchers to ensure reliability. The cost-benefit analysis is conducted using a 10-year projection, applying a social discount rate of 10% consistent with recommendations for public investment analysis in developing economies and drawing on human capital wage-premium estimates from Nigerian labour market data and international comparators.

Results

Research Question 1: What is the current state of STEM academic performance, science motivation, and student engagement among secondary school students in the study area?

Table 1: baseline level of STEM academic performance, science motivation, and student engagement among secondary school students

STEM Academic Performance	Lagos (n = 240)	Kano (n = 240)	Enugu (n = 240)	Overall (N = 720)
Mean STEM Score (%)	43.1	39.8	41.0	41.3
Standard Deviation	10.9	12.2	11.8	11.7
Science Motivation (SMQ-II)				

Source: Researchers Computation, 2026

Baseline assessments administered prior to the intervention reveal a pattern of STEM performance consistent with national trends documented in the literature. The mean pre-intervention score across all four STEM subjects (biology, chemistry, physics, and

mathematics) was 41.3% (SD = 11.7) for the combined sample, with marginal differences across the three study states (Lagos: M = 43.1%, SD = 10.9; Kano: M = 39.8%, SD = 12.2; Enugu: M = 41.0%, SD = 11.8). These scores are broadly representative of national

WAEC averages over the preceding three examination cycles, providing confidence in the sample's external validity.

Engagement scores measured through the SMQ-II prior to the intervention indicated moderate levels of science motivation ($M = 3.1$ on a 5-point Likert scale, $SD = 0.74$), with particularly low scores on the intrinsic motivation and self-determination subscales

($M = 2.8$ and $M = 2.7$, respectively). Qualitative baseline interviews with teachers and students corroborated these quantitative findings, with students consistently citing boredom, difficulty connecting abstract concepts to real-world applications, and a lack of relevant practical experiences as primary sources of disengagement from STEM subjects.

Table 2: Pre- and Post-Intervention Academic Performance by Subject (Experimental vs. Control Groups)

Subject	Control Pre	Control Post	Exp. Pre	Exp. Post	Effect Size (d)
Biology	40.2%	43.8%	41.0%	63.4%	0.92
Chemistry	39.7%	42.6%	40.1%	61.2%	0.83
Physics	41.5%	44.9%	42.3%	59.8%	0.81
Mathematics	43.9%	45.0%	43.8%	62.4%	0.90
Overall Average	41.3%	44.1%	41.8%	61.7%	0.87

Source: Researchers Computation, 2026

Post-intervention assessments reveal statistically significant and educationally meaningful improvements in academic performance for students in the VR/AR experimental group relative to controls. The mean post-intervention score for experimental group students was 61.7% ($SD = 9.4$), compared to 44.1% ($SD = 11.1$) for the control group, an increase of 20.4 percentage points and a statistically significant difference ($t(478) = 19.3$, $p < .001$). The Cohen's effect size of 0.87 indicates a large practical effect, substantially above the threshold of $d = 0.5$

considered educationally significant in educational intervention research (Hattie, 2009).

These findings are consistent with the global body of evidence reviewed in the study, affirming that VR- and AR-enhanced STEM instruction can produce significant learning gains, even in resource-constrained settings, when the intervention is carefully designed and pedagogically scaffolded. Notably, the effect sizes observed in the Nigerian context are comparable to and in some subjects exceed those reported in studies conducted in more

technologically endowed settings, suggesting that the relative deprivation of quality practical science experiences in Nigerian schools creates a particularly strong base effect for immersive technology interventions.

Engagement and motivation scores improved markedly for experimental group students. Post-intervention SMQ-II scores for the experimental group rose to a mean of 4.2 (SD = 0.61), compared to a minimal change to 3.3

(SD = 0.70) in the control group ($t(478) = 12.6$, $p < .001$, $d = 0.71$). The intrinsic motivation subscale showed the most pronounced improvement (from $M = 2.8$ to $M = 4.4$ in the experimental group), suggesting that VR and AR environments are particularly effective at stimulating the kind of self-directed, curiosity-driven engagement that is foundational to sustained STEM learning.

Research Question 2: What are the determinants of VR and AR technology adoption among students?

Table 3: Technology Acceptance and Diffusion of VR/AR Technologies among Students

Construct/Variable	Students	Teachers	Statistical Evidence
Perceived Usefulness (PU)	$\beta = 0.41^{***}$	$\beta = 0.33^{***}$	$p < .001$
Perceived Ease of Use (PEOU)	$\beta = 0.29^{***}$	$\beta = 0.38^{***}$	$p < .001$
Strongest Predictor of Adoption Intention	Perceived Usefulness	Perceived Ease of Use	Based on standardized β coefficients

***Note:** $^{**}p < .001$ indicates statistical significance at the 0.1% level. β = Standardized regression coefficient. TAM = Technology Acceptance Model; PU = Perceived Usefulness; PEOU = Perceived Ease of Use.

Source: *Researchers Computation, 2026*

TAM-based survey data reveal that both perceived usefulness (PU) and perceived ease of use (PEOU) were significant predictors of students' and teachers' intention to continue using VR and AR technologies. For students,

PU ($\beta = 0.41$, $p < .001$) was a stronger predictor of adoption intention than PEOU ($\beta = 0.29$, $p < .001$), suggesting that learners who perceive clear academic benefits from VR/AR engagement are more likely to sustain its use.

For teachers, PEOU ($\beta = 0.38$, $p < .001$) was a slightly stronger predictor than PU ($\beta = 0.33$, $p < .001$), reflecting teachers' practical concern that technology must be manageable within the demands of their instructional role.

Diffusion of Innovations analysis of qualitative data identified early adopters (approximately 22% of teachers) who expressed strong enthusiasm for VR/AR integration and actively sought to incorporate it into their practice beyond the formal intervention period. The

majority of teachers (54%) fell into the early majority category, expressing conditional support contingent on reliable technical infrastructure, ongoing professional development, and clear curricular guidance. A substantial minority (24%) remained sceptical or resistant, citing concerns about electricity reliability, content quality, and the perceived risk that technology will displace human pedagogical relationships.

Research Question 3: What is the economic viability of integrating VR and AR into STEM education in Nigeria?

Table 4: Cost-Benefit Analysis of VR/AR Integration in Nigerian STEM Education (10-Year Projection)

Cost/Benefit Category	Unit Estimate (₦)	10-Yr Total (₦)
Hardware (AR/smartphone per student, p.a.)	8,500	408,000,000
Hardware (VR headset per student, p.a.)	24,000	11,520,000
Content development (3 states, 5-yr lifecycle)	15,000,000	90,000,000
Teacher professional development	180,000/teacher	43,000,000
Maintenance & support	10% hardware p.a.	156,000,000
Total Costs (PV @ 10% discount rate)		1,849,000,000
Estimated wage premium (improved STEM grad)	₦ 320,000 p.a.	3,840,000,000
Workforce productivity gains (employer side)	15% productivity uplift	2,100,000,000
Reduced remediation/re-training costs	₦80,000/student	640,000,000
Total Benefits (PV @ 10% discount rate)		6,580
Net Present Value (NPV)		4,731,000,000
Benefit-Cost Ratio (BCR)		3.56:1

Source: Researcher's Computation, 2026

The analysis yields a Benefit-Cost Ratio (BCR) of 3.56:1, indicating that for every

Nigerian Naira invested in VR and AR integration in STEM education, the projected

economic return, principally through improved workforce productivity, enhanced graduate wage premiums and avoided remediation costs, is approximately ₦3.56 over a 10-year horizon. The Net Present Value (NPV) of the investment is estimated at ₦4.73 billion, discounted at 10%. These figures are

conservative in that they do not capture second-order economic effects, including innovation spillovers, increased attraction of foreign direct investment to technology-intensive sectors, and the social returns to improved health and civic literacy associated with higher educational attainment.

Discussion of Findings

The findings of this study indicate that the baseline level of STEM academic performance among secondary school students in the study area was generally low, with an overall mean score of 41.3%. Science motivation was only moderate, whereas intrinsic motivation and self-determination were relatively weak, suggesting limited enthusiasm for STEM learning prior to the intervention. These findings corroborate previous studies that attribute poor STEM outcomes in Nigeria to inadequate practical learning opportunities, teacher-centred instructional approaches, and limited student engagement. The qualitative evidence further reinforces this position, as students reported boredom and difficulty relating abstract scientific concepts to real-life situations.

Following the implementation of the VR/AR intervention, students in the experimental group demonstrated substantial improvements

in academic performance across all STEM subjects, achieving an overall post-test mean score of 61.7% compared with 44.1% for the control group. The large effect size (Cohen's $d = 0.87$) confirms that immersive technologies have a significant educational impact. Similarly, motivation for science improved considerably, particularly intrinsic motivation, indicating that VR/AR environments promote curiosity, active participation, and meaningful learning experiences. These findings are consistent with constructivist learning theory and previous empirical studies, which emphasize that immersive and interactive learning environments enhance conceptual understanding and academic achievement.

The study further revealed that perceived usefulness and perceived ease of use significantly influenced the adoption of VR and AR technologies. For students, perceived usefulness emerged as the strongest predictor of continued use, implying that learners are

more likely to adopt educational technologies when they perceive clear academic benefits. Conversely, teachers placed greater emphasis on perceived ease of use, reflecting the importance of technologies that integrate seamlessly into classroom practice. The diffusion analysis also showed that while a small proportion of teachers readily embraced the innovation, the majority expressed willingness to adopt it provided adequate infrastructure, training, and curriculum support were available. This finding aligns with the Technology Acceptance Model and Diffusion of Innovations Theory, both of which highlight perceived benefits, usability, and organizational support as key determinants of technology adoption.

Finally, the economic analysis demonstrates that integrating VR and AR into STEM education is financially viable in the Nigerian context. The estimated Benefit-Cost Ratio of 3.56:1 and a Net Present Value of ₦4.731 billion indicate that the long-term economic benefits substantially outweigh the implementation costs. Beyond improving students' academic outcomes, the projected gains in workforce productivity and graduate earnings, and the reduction in remediation costs, provide strong economic justification for investing in immersive educational technologies. These findings suggest that

strategic investment in VR/AR-supported STEM education can contribute significantly to Nigeria's human capital development and long-term economic competitiveness.

Conclusion

This study examined the integration of Virtual Reality and Augmented Reality into STEM education in Nigeria, synthesising global empirical evidence, primary research findings, and economic analysis within a theoretically grounded conceptual framework. The evidence gathered is unambiguous in its direction: VR and AR-enhanced STEM instruction can produce large, statistically significant, and educationally meaningful improvements in student engagement, knowledge acquisition, and competency development, even within the resource-constrained conditions typical of Nigerian secondary education. The cost-benefit analysis establishes a robust economic case for scaled investment in these technologies, with projected returns of ₦3.56 for every Naira invested over a 10-year horizon.

At the same time, the study underscores that the transformative potential of VR and AR is not realised automatically through the deployment of technology alone. Contextual adaptation of content, robust teacher professional development, attention to

infrastructure preconditions, and careful pedagogical scaffolding are necessary complements to hardware and software investment. A technology-first strategy that neglects these human and institutional factors is unlikely to deliver the learning and economic dividends that the evidence suggests are achievable.

The study contributes to the scholarly literature by providing one of the first systematic empirical investigations of VR and AR effectiveness in Nigerian STEM education, offering a contextually validated implementation framework, and generating evidence-based economic projections that can inform public investment decisions. The findings are generalisable, with appropriate contextual adaptation, to other sub-Saharan African and developing-economy educational systems that share the structural and infrastructural characteristics documented in this study.

Recommendations

1. Governments should incorporate VR and AR integration into national STEM education strategies and medium-term sector plans, with dedicated budget allocations for hardware procurement, content development, and teacher training.
2. There should be public-private partnerships with Nigerian telecommunications providers and technology firms should be actively cultivated to reduce technology costs and leverage private sector innovation capacity.
3. Curriculum developers should ensure that VR and AR content is explicitly aligned with the Nigerian National Curriculum and assessed within the existing examination framework.
4. School administrators should create structured opportunities for teachers to observe VR/AR lessons, participate in communities of practice and share pedagogical experiences leveraging the observability and social proof mechanisms.
5. Development partners such as UNICEF, the World Bank, the African Development Bank and bilateral donors should consider VR and AR integration in STEM education as a high-priority investment area within education sector programming in Nigeria.
6. Future research should address key gaps identified in this study, including longitudinal tracking of the labour

market outcomes of students who received VR/AR-enhanced STEM instruction; controlled evaluation of specific VR/AR content designs and pedagogical scaffolding approaches; investigation of gender-differentiated effects of immersive technology on STEM outcomes and exploration of the potential for community-based VR/AR access models such as mobile VR labs serving clusters of schools to extend the reach of immersive technology to the most resource-constrained communities.

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