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Effect of Artificial Intelligence Tools on Achievement in Complex STEM Concepts among Senior Secondary School Students in Ilorin, Kwara State, Nigeria

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Abstract

The integration of Artificial Intelligence (AI) into secondary education presents a significant opportunity to address persistent challenges in Science, Technology, Engineering, and Mathematics (STEM) instruction in Nigeria. This study investigated the effect of AI tools on the learning of complex STEM concepts among Senior Secondary School II (SS2) students in Ilorin, Kwara State. Using a quasi-experimental pre-test, post-test non-equivalent control group design, 360 SS2 students were drawn from six purposively selected schools across Ilorin West, East, and South Local Government Areas. The experimental group (n = 180) received AI-enhanced instruction using uLesson, PhET Interactive Simulations, and ChatGPT, while the control group (n = 180) was taught using conventional lecture-based methods. Data were collected using a validated 40-item STEM Achievement Test (SAT; KR-20 = 0.82) and an AI Integration Questionnaire (AIQ). Descriptive statistics (mean, standard deviation) and Analysis of Covariance (ANCOVA) were employed for data analysis at a 0.05 significance level. Findings revealed that the AI-enhanced group achieved a significantly higher post-test mean score (74.50) compared to the control group (56.20), yielding a mean gain of 32.35 against 14.40 for the control, with ANCOVA confirming statistical significance [$F(1, 357) = 142.31, p < .05$]. Students and teachers reported that virtual simulations effectively substituted for absent physical laboratory facilities. However, high internet data costs and frequent power outages were identified as critical barriers to sustained adoption. The study concludes that AI tools significantly demystify complex STEM topics by providing interactive scaffolding and personalised feedback and recommends targeted infrastructure investment, subsidised data access, and institutionalised AI-literacy training for STEM teachers in Kwara State.

Keywords: *Artificial Intelligence, STEM education, virtual simulations, adaptive learning and students*

Introduction

The mastery of Science, Technology, Engineering, and Mathematics (STEM) subjects is widely regarded as foundational to national development, technological innovation, and economic competitiveness in the twenty-first century (Aina, 2022). For Nigeria to participate meaningfully in the global digital economy, its young population must acquire deep conceptual understanding of scientific and mathematical principles that underpin modern technological enterprise. Yet, despite this national imperative, STEM education in Nigerian senior secondary schools remains beset by well-documented structural and pedagogical challenges that impede student learning and attainment (Odeyemi & Ayilara, 2021). In Ilorin, the capital of Kwara State and a significant educational hub in north-central Nigeria, secondary school students consistently struggle with abstract STEM concepts, particularly in subjects such as Physics, Further Mathematics, Organic Chemistry, and Differential Calculus. These difficulties are compounded by a reliance on rote-based, teacher-centred instructional methods; a critical shortage of functional laboratory facilities in many public and mission schools; high student-teacher ratios that preclude individualised attention; and a growing disconnect between the analogue realities of local classrooms and the digital demands of twenty-first-century STEM careers (Oladokun & Adeniran, 2024; Luwoye et al., 2024). The resulting learning deficits manifest in inconsistent performance in the West African Senior School Certificate Examination (WASSCE) and the Joint Admissions and Matriculation Board (JAMB) examinations, with cascading consequences for students' prospects of accessing tertiary education and high-skilled employment. The emergence of Artificial Intelligence



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(AI) technologies offers a potentially transformative response to these structural challenges. AI-powered educational tools , including adaptive learning platforms, intelligent tutoring systems (ITS), and virtual laboratory simulations provide personalised, interactive, and data-driven learning experiences that can cater to students' individual cognitive needs, compensate for absent physical resources, and bridge the gap between abstract theoretical content and concrete conceptual understanding (Akinyemi et al., 2023; Ibrahim-Abdullateef et al., 2024). As Luwoye et al. (2024) observe, the integration of AI into the Nigerian educational system creates an opportunity to transcend conventional instructional boundaries, enabling more interactive and responsive engagement with complex curriculum content. In resource-constrained contexts such as Ilorin, where many schools cannot provide the laboratory equipment necessary for practical STEM instruction, AI-driven virtual simulations represent a particularly promising alternative (Oladokun & Adeniran, 2024).

The theoretical rationale for AI in STEM education draws on two well-established frameworks. Cognitive Load Theory (Sweller, 1988, as cited in Omodara et al., 2024) posits that effective instruction must minimise the extraneous cognitive load imposed by poorly designed learning materials, thereby freeing working memory for meaningful schema construction. AI tools operationalise this principle by decomposing complex topics such as Quantum Physics or Organic Chemistry into sequenced, visually supported modules that scaffold learners' progression from foundational to advanced understanding. Constructivism (Piaget, as cited in Odeyemi & Ayilara, 2021) further supports the use of AI by emphasising the role of active experimentation and discovery in knowledge construction: interactive AI environments enable students to manipulate variables, observe consequences, and build conceptual understanding through inquiry-oriented engagement rather than passive reception of information. Despite the growth of research on Information and Communication Technology (ICT) in Nigerian education, empirical evidence specifically examining the effect of AI tools on STEM learning outcomes among secondary school students in Kwara State remains limited (Babalola et al., 2024; Oladokun & Adeniran, 2024). Most existing studies focus on higher education institutions in cities such as Lagos and Abuja, leaving secondary-level outcomes in north-central Nigeria largely uncharted. Ilorin's distinctive educational landscape, characterised by a concentration of federal, state, private, and religious mission schools with markedly different funding levels and resource profiles, makes it an especially important context for investigating how AI adoption intersects with socioeconomic inequality to shape student outcomes. Furthermore, the digital divide in Ilorin introduces an equity dimension that complicates the straightforward adoption of AI tools. While elite private schools have begun integrating platforms such as uLesson and Khan Academy, many public institutions continue to rely on textbooks and chalk-and-talk methods, with limited or no access to digital infrastructure (Ibrahim-Abdullateef et al., 2024). High internet data costs, frequent power outages, and limited teacher capacity for AI-facilitated instruction present significant barriers to equitable access (Luwoye et al., 2024). As noted by Ibrahim-Abdullateef et al. (2024), teacher and student attitudes towards AI constitute a critical determinant of implementation success, yet these attitudinal dimensions have been insufficiently explored in the Ilorin context. This study therefore addresses a critical and timely gap in the literature by providing empirical, contextually grounded evidence on the effect of AI tools on complex STEM learning among senior secondary students in Ilorin. The findings are intended to inform educational policy, guide curriculum reform, and support the development of evidence-based, equity-sensitive strategies for AI integration in Kwara State secondary schools.

Objectives of the Study

The primary aim of this study is to empirically assess the effect of Artificial Intelligence tools on the learning of complex STEM concepts among Senior Secondary School II (SS2) students in Ilorin, Kwara State, Nigeria. The study specifically:

1. evaluated the effectiveness of AI-enhanced instruction compared to conventional teaching in improving students' understanding of complex STEM concepts.
2. evaluate students' perceived usefulness and accessibility of AI tools in the Ilorin metropolis
3. identified the specific technical and economic barriers that hinder the effective use of AI tools for STEM instruction in selected secondary schools in Ilorin
4. assessed STEM teachers' perception on AI-assisted instruction

Research Questions

The following research questions guided the investigation:



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1. Is there a significant difference in the mean STEM achievement scores of SS2 students taught using AI tools and those taught using traditional instructional methods in Ilorin secondary schools?
2. What extent are AI learning tools available and actively accessible to senior secondary school students within the Ilorin metropolis?
3. What are the primary technical, economic, and infrastructural barriers preventing the effective integration of AI tools into STEM classrooms in Ilorin?
4. How do STEM teachers in Ilorin perceive the role of AI tools in enhancing their instructional efficiency and supporting personalised student learning?

Research Hypotheses

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

H₀₁: There is no significant difference in the mean STEM achievement scores of students taught using AI tools and those taught using conventional methods in the selected secondary schools in Ilorin.

H₀₂: There is no significant relationship between students' socioeconomic background and their ability to utilise AI tools for STEM learning in Ilorin effectively.

Literature Review

Artificial Intelligence Tools in STEM Education

The integration of Artificial Intelligence into education represents a fundamental paradigm shift from static, teacher-centred instructional delivery to dynamic, data-driven, and learner-responsive environments. AI tools in education are broadly defined as software systems that deploy advanced algorithms to simulate human cognitive processes, including pattern recognition, natural language processing, and adaptive problem-solving, in order to support both teachers and students (Ibrahim-Abdullateef et al., 2024). In the context of STEM education in Ilorin, these tools manifest in three principal forms that are directly relevant to the challenges identified in this study. Adaptive learning platforms, such as uLesson and Khan Academy, automatically calibrate the difficulty and sequencing of instructional content based on individual learner performance, ensuring that students consolidate algebraic foundations before advancing to calculus and that physics principles are mastered before complex problem-solving is attempted (Akinyemi et al., 2023). Intelligent tutoring systems (ITS), including ChatGPT and Socratic, function as continuously available personal tutors, providing step-by-step conceptual explanations, worked examples, and immediate corrective feedback on scientific equations and mathematical proofs. Virtual laboratory simulations, most notably PhET Interactive Simulations developed by the University of Colorado Boulder, allow students to conduct interactive experiments in Chemistry and Physics within a digital environment, offering a pedagogically viable substitute for physical laboratory apparatus in schools where such facilities are absent or inadequate (Oladokun & Adeniran, 2024; Aina, 2022). The pedagogical complementarity of these three categories of AI tools makes them particularly suitable for the resource-constrained secondary school context of Ilorin, where the intersection of infrastructure deficits and complex STEM curriculum demands creates a clear need for technologically mediated instructional support.

Theoretical Framework

This study is grounded in two complementary learning theories that collectively justify the pedagogical utility of AI tools in STEM education. Cognitive Load Theory, developed by Sweller (1988) and elaborated by subsequent scholars (Omodara et al., 2024), distinguishes between intrinsic cognitive load, the inherent complexity of the material itself, and extraneous cognitive load, which arises from poorly designed instructional materials that impose unnecessary mental effort on learners. AI tools reduce extraneous load by presenting complex STEM topics, such as Quantum Physics, Organic Chemistry, and Differential Calculus, as visually structured, incrementally scaffolded modules that align instructional complexity with learners' current knowledge states. This careful management of cognitive demand is particularly crucial in secondary school STEM contexts, where the hierarchical structure of the curriculum means that conceptual gaps at foundational levels propagate into persistent difficulties at higher levels of complexity (Luwoye et al., 2024).

Constructivist learning theory, associated principally with Piaget and Vygotsky (as cited in Odeyemi & Ayilara, 2021), provides the second theoretical pillar. Constructivism holds that learners do not passively receive knowledge but actively



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construct it through experiential engagement, inquiry, and social interaction. AI tools operationalise constructivist principles by creating interactive environments in which students can manipulate variables, observe outcomes, test hypotheses, and build conceptual understanding through active discovery rather than passive reception. Virtual laboratory simulations, in particular, embody this principle by enabling students to conduct controlled experiments, observing the consequences of varying temperature, concentration, or resistance, for instance, in ways that standard classroom instruction cannot replicate. Together, these two theoretical frameworks establish a robust pedagogical rationale for the use of AI tools as instruments of deep, sustained STEM learning in the Ilorin context.

Empirical Evidence on AI and STEM Learning in Nigeria

A growing body of empirical research documents the impact of digital and AI-mediated instruction on academic achievement in Nigerian educational settings. Akinyemi et al. (2023) demonstrated that AI-driven simulations improved STEM achievement scores by up to 30% in resource-constrained Nigerian secondary schools, attributing these gains principally to the scaffolded visualisation of abstract concepts and the provision of immediate personalised feedback. Omodara et al. (2024) corroborated these findings in a study of cognitive load management, showing that AI-driven scaffolding significantly reduced the extraneous cognitive load experienced by students engaging with complex physics and chemistry problems, thereby freeing working memory for deeper conceptual processing. In Nigerian higher education, Ibrahim-Abdullateef et al. (2024) found that while awareness of AI tools is high among academic staff, adoption for substantive instructional engagement remains limited due to infrastructural constraints, attitudinal barriers, and a lack of institutional support, findings that carry direct implications for secondary-level implementation in Ilorin. Oyelere et al. (2023) demonstrated the effectiveness of AI-enhanced engineering projects in improving STEM competencies among Nigerian secondary school learners, while Ogwo (2023) documented the positive impact of AI integration in academic libraries in terms of improving research efficiency and information literacy among students in south-western Nigeria. Gender equity considerations have also emerged as an important dimension of AI-STEM research in Nigeria: UNESCO (2024) evaluated the Inspiring Girls Now In Technology Evolution (IGNITE) initiative, finding that targeted digital interventions significantly increased female students' interest and participation in STEM disciplines, a finding that underscores the equity potential of well-designed AI-mediated instruction. Babalola et al. (2024) specifically examined teacher AI self-efficacy in Kwara State secondary schools, identifying a strong positive relationship between teachers' confidence in using AI tools and the quality of their instructional delivery, a finding that highlights the importance of teacher training as a precondition for effective AI integration.

Research Gap

While the foregoing body of research provides important foundations, a critical localised gap persists in the literature regarding the effect of AI tools specifically on STEM learning outcomes at the secondary school level in Kwara State. The majority of Nigerian AI-in-education studies are concentrated in higher education institutions in major metropolitan centres such as Lagos and Abuja (Oladokun & Adeniran, 2024), and few address the distinctive educational landscape of Ilorin, where federal government colleges, Kwara State secondary schools, private institutions, and religious mission schools coexist within a context of pronounced socioeconomic inequality. In particular, no prior study has provided controlled experimental evidence on the comparative effectiveness of AI tools versus conventional methods for teaching complex STEM concepts, such as Organic Chemistry, Quantum Physics, and Differential Calculus, to SS2 students in Ilorin. Furthermore, the interaction between AI adoption and the specific infrastructural barriers of the region, including power supply instability and high data costs, has not been empirically examined at the secondary level. This study addresses all of these gaps directly.

Methodology

Research Design

This study adopted a quasi-experimental pre-test, post-test non-equivalent control group design. This design was selected as the most appropriate for the natural school setting in Ilorin, as it permitted the rigorous assessment of AI tools' effect on learning outcomes without disrupting existing classroom groupings or school timetables. The experimental group received AI-enhanced STEM instruction over a six-week intervention period, while the control group was concurrently taught the same curriculum content using conventional lecture-based methods. A descriptive survey component was additionally integrated to collect data on students' attitudes, perceived barriers, and user experiences with AI tools, as well as teachers'



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perceptions of AI-assisted instruction. This mixed-instrument approach strengthened the study's capacity to address both its experimental and descriptive research questions within a unified, coherent design.

Population and Sampling

The target population comprised all SS2 students enrolled in registered secondary schools in the Ilorin metropolis, covering Ilorin West, Ilorin East, and Ilorin South Local Government Areas (LGAs). Based on data from the Kwara State Ministry of Education, the population comprised approximately 43,000 SS2 students across the three LGAs. A multi-stage sampling procedure was employed. In the first stage, schools were stratified by ownership type, public (government), private, and religious mission, to reflect the socioeconomic diversity of Ilorin's secondary education landscape. In the second stage, six schools (two per LGA) were purposively selected based on the availability of basic ICT infrastructure, including internet connectivity and electricity supply, as minimum preconditions for AI tool use. In the third stage, 60 students were randomly selected from each school using simple random sampling, yielding a final sample of 360 SS2 students (180 per group). The deliberate selection of SS2 students was justified by their placement at a critical juncture in the STEM curriculum, when they engage with particularly complex topics, including Organic Chemistry and Integral Calculus, that are known to generate high levels of cognitive difficulty and examination underperformance.

Instrumentation

Two primary instruments were developed and validated for data collection in this study. The STEM Achievement Test (SAT) was a 40-item multiple-choice instrument covering complex concepts in Physics (including mechanics, optics, and electromagnetism), Chemistry (with emphasis on organic reactions and thermochemistry), and Mathematics (focusing on calculus and statistics). Items were constructed in alignment with the Nigerian national secondary school curriculum and were subjected to face and content validity assessment by a panel of six subject matter experts drawn from the Departments of Educational Technology, Science Education, and Life Science Education at the University of Ilorin and Kwara State University. The instrument was pilot-tested on 50 SS2 students outside the main sample, and reliability was established using the Kuder-Richardson Formula 20 (KR-20), which yielded a reliability index of 0.82, exceeding the minimum threshold of 0.70 for research instruments (Babalola et al., 2024). The AI Integration Questionnaire (AIQ) was a Likert-scale instrument (1 = Strongly Disagree, 5 = Strongly Agree) designed to measure student engagement with AI tools, perceived ease of use, and the nature and severity of access barriers, including data costs and power supply instability. A parallel teacher version of the AIQ assessed STEM teachers' perceptions of AI's impact on instructional efficiency, workload management, and their capacity to provide personalised student support.

Data Collection Procedure

Data collection was conducted over a six-week period during the 2024–2025 academic session, following receipt of ethical approval from the relevant school authorities and informed consent from all participating students and teachers. The procedure unfolded in three sequential phases. In the Pre-test Phase (Week 1), the SAT was administered to both the experimental and control groups to establish baseline equivalence in prior STEM knowledge. The pre-test results confirmed near-identical starting scores across the two groups (experimental: $\bar{x} = 42.15$; control: $\bar{x} = 41.80$), validating the non-equivalent group design. During the Treatment Phase (Weeks 2–5), the experimental group was taught selected complex STEM topics using uLesson for adaptive video content and personalised revision modules; PhET Interactive Simulations for virtual physics and chemistry experiments; and ChatGPT for step-by-step mathematical problem-solving and conceptual clarification. The control group received instruction on the same topics and for an equivalent duration through the traditional lecture method, supported by standard textbooks and chalk-board demonstrations. In the Post-test Phase (Week 6), the SAT was re-administered to both groups to measure learning gains, and the AIQ was distributed to the experimental group students and all participating teachers to capture their experiences and perceptions of the AI-enhanced intervention.

Data Analysis

Quantitative data were analysed using IBM SPSS Statistics. Descriptive statistics, specifically means and standard deviations, were computed to answer the research questions relating to performance differentials and attitudinal perceptions. To test the null hypotheses, the Analysis of Covariance (ANCOVA) was employed at a 0.05 significance level, with the pre-test score as the covariate, in order to statistically control for any residual baseline differences between the two groups and thereby isolate the treatment effect attributable to AI-enhanced instruction. Pearson's product-moment correlation was used to examine the relationship between students' socioeconomic background (as assessed through the



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AIQ) and their AI tool utilisation scores, in order to test H_{02} . Effect sizes were computed using partial eta-squared (η^2) to assess the practical significance of the ANCOVA results alongside their statistical significance.

Presentation of Results

The findings of this study were derived from analysis of the STEM Achievement Test (SAT) pre-test and post-test data, the ANCOVA results for hypothesis testing, and the descriptive analysis of the AI Integration Questionnaire (AIQ) responses from students and teachers. Results are presented in the order of the research questions and hypotheses.

Research Question 1: Comparative Academic Performance

Table 1 presents the descriptive statistics comparing the pre-test and post-test mean achievement scores of the experimental (AI-enhanced) and control (conventional) groups.

Table 1: Comparison of Pre-test and Post-test Mean Achievement Scores

Group	N	Pre-test Mean (\bar{x})	Post-test Mean (\bar{x})	Mean Gain	SD (Post-test)
Experimental (AI-Enhanced)	180	42.15	74.50	32.35	8.12
Control (Conventional)	180	41.80	56.20	14.40	10.45

As shown in Table 1, the two groups entered the study with virtually equivalent prior knowledge, a pre-test mean score difference of only 0.35 points, confirming baseline comparability. Following the six-week intervention, the experimental group achieved a post-test mean of 74.50, representing a mean gain of 32.35 points, while the control group achieved a post-test mean of 56.20, representing a mean gain of 14.40 points. The AI-enhanced group's mean gain was therefore more than double that of the control group, providing initial descriptive evidence of the superior instructional effectiveness of AI tools for complex STEM learning.

Hypothesis Testing (H_{01})

To determine whether the observed performance differential was statistically significant, an ANCOVA was performed with the pre-test score as the covariate. The result yielded $F(1, 357) = 142.31, p < .001$, partial $\eta^2 = .29$. Since the p-value was well below the 0.05 significance threshold and the partial eta-squared value indicated a large effect (Cohen, 1988, as cited in Babalola et al., 2024), H_{01} was rejected. This finding confirms that AI tools exerted a statistically significant and practically meaningful positive effect on the learning of complex STEM concepts among SS2 students in Ilorin, beyond what could be attributed to pre-existing differences in prior knowledge.

Research Questions 2 and 3: Student Perceptions

Table 2 presents the descriptive findings from the student AIQ, addressing the accessibility of AI tools and the barriers to their sustained use.

Table 2: Student Perceptions and Challenges of AI Tool Integration (N = 180)

S/N	Item Description	Mean (\bar{x})	Interpretation
1	AI tools simplified abstract concepts such as Calculus and Organic Chemistry.	4.45	Strongly Agree
2	Virtual laboratory simulations provided better conceptual understanding than theoretical notes alone.	4.60	Strongly Agree
3	Immediate AI feedback helped me identify and correct my errors promptly.	4.38	Agree
4	High cost of internet data limited my use of AI tools outside school hours.	4.25	Agree
5	Frequent power outages disrupted my ability to access AI-enabled learning materials.	4.10	Agree



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6	I feel more confident and capable in solving STEM problems after using AI tutoring tools.	4.52	Strongly Agree
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The AIQ findings reveal a compelling contrast between strong pedagogical satisfaction and persistent structural barriers. Items 1, 2, and 6 all attracted mean scores in the 'Strongly Agree' range (4.38–4.60), confirming that students widely perceived AI tools as effective instruments for simplifying abstract STEM concepts, providing experiential learning analogous to laboratory practice, and building self-efficacy in STEM problem-solving. Notably, Item 2 recorded the highest mean score (4.60), reflecting the particular value students assigned to virtual laboratory simulations as substitutes for absent physical facilities, a finding consistent with the broader literature on AI in resource-constrained contexts (Oladokun & Adeniran, 2024). Against these gains, Items 4 and 5 confirm that high data costs ($\bar{x} = 4.25$) and power instability ($\bar{x} = 4.10$) constitute significant and widely experienced barriers to home-based AI learning, underscoring the digital divide challenge identified in the problem statement.

Research Question 4: Teachers' Perceptions of AI-Enhanced Instruction

Table 3 presents the findings from the teacher perception component of the AIQ (N = 12 STEM teachers from the six participating schools).

Table 3: STEM Teachers' Perceptions of AI-Enhanced Instruction (N = 12)

S/N	Item Description	Mean (\bar{x})	Interpretation
1	AI tools reduced the time I spend on repetitive drills, marking, and remedial explanation.	4.32	Agree
2	Using AI simulations enabled me to explain abstract STEM topics more effectively than traditional methods.	4.65	Strongly Agree
3	AI tools allowed me to devote more time to personalised support for students who were struggling.	4.15	Agree
4	I feel sufficiently confident in my ability to plan and facilitate AI-driven STEM lessons.	3.80	Agree

Teacher perceptions of AI-enhanced instruction were uniformly positive, though with a nuanced pattern. Item 2 attracted the highest mean score (4.65, 'Strongly Agree'), confirming that AI simulations significantly enhanced teachers' capacity to make abstract STEM topics accessible, the central pedagogical purpose of the intervention. Items 1 and 3 (mean scores of 4.32 and 4.15, respectively) indicate that AI tools effectively redistributed teachers' instructional time, reducing the burden of repetitive tasks and enabling more targeted engagement with struggling learners. Importantly, Item 4 ($\bar{x} = 3.80$) reveals a modest but meaningful gap in teacher self-efficacy with respect to AI-facilitated lesson planning and delivery, pointing to the need for structured, institutionalised AI-literacy professional development as a prerequisite for sustainable adoption. These findings collectively indicate that AI tools are perceived not as replacements for teachers but as powerful pedagogical amplifiers that enhance professional effectiveness.

Hypothesis Testing (H₀₂)

Pearson's product-moment correlation was used to examine the relationship between students' self-reported socioeconomic background (operationalised as access to personal devices and home internet) and their AI tool utilisation scores on the AIQ. The analysis yielded $r(178) = .68, p < .05$, indicating a moderate-to-strong positive correlation. Accordingly, H₀₂ was rejected. This finding confirms that students from lower socioeconomic households, characterised by limited home device access and inability to afford data subscriptions, were significantly less able to utilise AI tools effectively for STEM learning, despite benefiting from school-based access during the intervention period.

Discussion of Findings

The findings of this study converge on a clear central conclusion: AI-enhanced instruction is significantly and substantially more effective than conventional lecture-based teaching in improving senior secondary students' mastery of complex STEM concepts in Ilorin, Kwara State. The ANCOVA result [$F(1, 357) = 142.31, p < .001, \text{partial } \eta^2 = .29$] represents a large treatment effect by conventional benchmarks, and the near-doubling of mean learning gains in the experimental group (32.35 vs. 14.40) provides compelling evidence of the transformative instructional potential of AI tools in this context.



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This primary finding is directly explicable through the lens of Cognitive Load Theory. The AI tools deployed in this study, particularly PhET Interactive Simulations and ChatGPT, operationalised the theory's core prescription by restructuring complex STEM content into visually scaffolded, sequentially presented modules that reduced extraneous cognitive load while directing students' limited working memory resources toward the construction of meaningful, transferable schemas (Omodara et al., 2024; Luwoye et al., 2024). Students' strong endorsement of virtual laboratory simulations ($\bar{x} = 4.60$) is particularly significant in the Ilorin context, where the absence of functional physical laboratories in many public schools has historically been a major driver of student disengagement and underperformance in practical science subjects. The finding that AI-driven virtual labs can effectively substitute for absent physical facilities corroborates the conclusions of Akinyemi et al. (2023) and Oladokun and Adeniran (2024), who identified digital simulations as a viable and cost-effective response to Nigeria's laboratory infrastructure deficit. The constructivist dimension of the AI intervention was also evident in students' significantly enhanced self-efficacy scores ($\bar{x} = 4.52$): the active, inquiry-oriented nature of virtual simulation environments, in which students can manipulate variables, test predictions, and observe real-time consequences, appears to have promoted the kind of experiential discovery that constructivist theory identifies as the foundation of deep, durable conceptual understanding (Odeyemi & Ayilara, 2021). This active engagement stands in sharp contrast to the passive reception of information characteristic of conventional chalk-and-talk instruction and may, in part, account for the magnitude of the experimental group's learning advantage. The rejection of H_{02} ($r = .68, p < .05$) introduces an important equity caveat to these positive findings. The significant positive correlation between students' socioeconomic background and their AI tool utilisation efficiency confirms that the digital divide is not merely a matter of school-level infrastructure but extends into students' domestic environments, where high data costs and unreliable power supply constrain after-hours AI-enabled learning (Luwoye et al., 2024). Students from lower-income households in Ilorin West and East who lacked personal devices or could not afford data subscriptions were unable to extend their engagement with AI learning tools beyond the supervised school setting, a limitation that risks exacerbating rather than ameliorating existing educational inequalities if left unaddressed by policy. This finding echoes the caution raised by Ibrahim-Abdullateef et al. (2024) and Oladokun and Adeniran (2024) regarding the differential benefits of digital integration across socioeconomic strata in Nigerian education. The teacher perception data provide a further layer of nuance. The finding that AI tools were perceived as reducing repetitive instructional burden ($\bar{x} = 4.32$) while enabling more personalised student support ($\bar{x} = 4.15$) is consistent with Omodara et al.'s (2024) conceptualisation of AI as a pedagogical co-facilitator rather than a teacher replacement. Crucially, the modest teacher self-efficacy score ($\bar{x} = 3.80$) on item four signals that, while teachers value AI tools and perceive their benefits, they do not yet feel fully prepared to independently design and deliver AI-facilitated lessons, a finding that aligns with Babalola et al.'s (2024) identification of teacher AI self-efficacy as a critical mediator of instructional quality. This points unambiguously to the need for structured, sustained, and institutionalised professional development as a non-negotiable precondition for scaling AI integration in Kwara State secondary schools.

Conclusion

This study provides robust empirical evidence that AI tools significantly enhance the learning of complex STEM concepts among Senior Secondary School II students in Ilorin, Kwara State. By deploying adaptive platforms, intelligent tutoring systems, and virtual laboratory simulations within a controlled quasi-experimental design, the study demonstrates that AI-enhanced instruction produces learning gains more than double those achievable through conventional lecture-based methods, gains that are both statistically significant and educationally meaningful. Virtual simulations proved especially effective in bridging the gap created by the absence of physical laboratory facilities in many Ilorin public schools, confirming AI's potential as an equity-sensitive instrument for improving STEM access and quality in resource-constrained contexts. However, the study's findings equally highlight the structural conditions that must be addressed if the benefits of AI tools are to be equitably distributed. The digital divide, manifested through high internet data costs, power supply instability, and inequitable home access to devices, remains a significant barrier that risks confining AI's benefits to more advantaged students and institutions. Furthermore, a modest gap in teacher self-efficacy for AI-facilitated instruction identifies structured professional development as an urgent priority. Taken together, these findings call for a coordinated policy response that addresses both the technology infrastructure deficits and the human capacity constraints that currently limit the reach and sustainability of AI integration in Kwara State secondary education. AI is not a replacement for teachers in Ilorin, but a powerful and evidence-based pedagogical catalyst that, given the right policy support and infrastructure,



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has the potential to transform STEM learning outcomes across the state and , by extension , to contribute to Nigeria's broader ambition of building a knowledge-driven, technologically capable workforce.

Recommendations

On the basis of the empirical findings, the following evidence-based recommendations are advanced:

1. The Kwara State Government and the Federal Ministry of Education should prioritise the establishment of solar-powered ICT hubs in public secondary schools across Ilorin West, East, and South, as a sustainable infrastructure solution to the power supply instability that currently restricts AI-enabled learning to electricity-dependent school hours.
2. The Ministry of Education, in partnership with the Nigerian Communications Commission (NCC), should negotiate zero-rated or heavily subsidised internet data access specifically for registered educational AI platforms , including uLesson, PhET, and equivalent tools , to remove the economic barrier to home-based AI learning among students from lower-income households.
3. STEM teacher training institutions, including the University of Ilorin Faculty of Education and the Kwara State Teacher Training College, should incorporate mandatory, hands-on AI-literacy modules into both pre-service and in-service professional development programmes, equipping teachers with the pedagogical skills and technical confidence necessary to design and facilitate AI-enhanced STEM lessons effectively.
4. The Kwara State Secondary Education Board should formally recognise virtual laboratory simulations conducted through validated platforms such as PhET as equivalent to physical practical assessments for the purposes of school-based continuous assessment, thereby legitimising and incentivising their institutional adoption.
5. Private sector stakeholders and corporate social responsibility initiatives operating in Ilorin should be engaged to sponsor AI-learning kits , comprising tablet devices and prepaid data plans, for high-achieving, economically disadvantaged students, as a targeted equity intervention to close the within-school digital divide.

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