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Harnessing Artificial Intelligence to Transform STEM and Integrated Science Education for Sustainable Development in Nigerian Secondary Schools

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Abstract

Artificial Intelligence (AI) is reshaping educational practices worldwide, yet its integration into secondary school STEM and Integrated Science classrooms in Nigeria remains limited. This study investigates the role of AI in enhancing student engagement, motivation, conceptual understanding, and sustainable development competencies in Nigerian secondary schools. Adopting a quasi-experimental design, 180 junior secondary students from three purposively selected public schools in Ikere Local Government Area, Ekiti State, were randomly assigned to experimental and control groups. AI-driven instructional tools, including virtual laboratories and intelligent tutoring systems, were employed in the experimental group, while traditional methods were used in the control group. Data were analyzed using descriptive statistics, paired and independent samples t-tests to evaluate differences in pre-test and post-test scores. Findings reveal that AI integration significantly improves student engagement, motivation, and academic performance, while also fostering skills essential for sustainable development, such as collaborative problem-solving and systems thinking. However, infrastructural limitations, digital literacy gaps among teachers, and resource constraints remain key barriers to effective implementation. The study concludes that strategic adoption of AI in secondary school science education can transform STEM learning, equipping students with knowledge and skills aligned with the Sustainable Development Goals (SDGs) and global sustainability priorities. The findings underscore the importance of targeted professional development for educators and investment in digital infrastructure, highlighting AI as a critical driver of educational innovation.

Keywords: Artificial Intelligence; STEM Education; Integrated Science; Sustainable Development; Student Engagement

1. Introduction

The rapid advancement of digital technologies has fundamentally reshaped educational systems worldwide, with Artificial Intelligence (AI) emerging as a transformative force in teaching and learning. Within the context of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education, AI offers unprecedented opportunities to enhance instructional delivery, promote personalized learning, and equip students with competencies required for addressing complex global challenges. Contemporary educational discourse increasingly emphasizes the integration of AI-driven tools such as intelligent tutoring systems, adaptive learning platforms, and virtual laboratories as essential mechanisms for fostering inquiry-based learning and improving student outcomes in science education (Okunade, 2024; Ahmed & Amao, 2025; Dimitriadou & Lanitis, 2023).

In many developing contexts, particularly in Nigeria, the need to transform STEM and Integrated Science education is both urgent and critical. Despite policy efforts aimed at strengthening science education, classrooms remain largely dominated by traditional, teacher-centered approaches characterized by rote memorization and limited student

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interaction. Such pedagogical practices have been widely criticized for their inability to develop higher-order thinking skills, creativity, and problem-solving abilities necessary for the 21st-century knowledge economy (Samuel & Salisu, 2025; Ayogu & Ogwu, 2025). Consequently, students often exhibit low engagement, poor conceptual understanding, and limited preparedness for careers in science and technology fields.

Artificial Intelligence presents a viable pathway for addressing these challenges by enabling adaptive, student-centered, and data-driven learning environments. AI-powered tools facilitate real-time feedback, automate assessment processes, and provide personalized learning experiences that cater to individual differences in learning pace and style. For instance, AI-driven simulations and virtual laboratories allow students to engage in safe, repeatable, and cost-effective experimentation, thereby overcoming the limitations of inadequate physical laboratory facilities commonly observed in resource-constrained schools (Ramli & Mahmud, 2025; Samuel & Salisu, 2025). In addition, machine learning applications have demonstrated the capacity to assess complex scientific reasoning and provide immediate feedback, thereby enhancing students' ability to refine their understanding through interative learning processes (Zhai et al., 2022).

The theoretical underpinning of this study is anchored in constructivist learning theory**,** which posits that learners actively construct knowledge through interaction, exploration, and reflection. AI technologies align strongly with this perspective by creating interactive learning environments that promote inquiry, experimentation, and collaborative problem-solving. Furthermore, insights from cognitive load theory suggest that AI-enhanced visualizations and simulations can reduce the mental burden associated with processing complex scientific concepts, thereby improving comprehension and retention. The integration of AI in education is also supported by the Technological Pedagogical Content Knowledge (TPACK) framework, which emphasizes the need for teachers to effectively combine subject knowledge, pedagogy, and technology to enhance instructional outcomes (Gibson et al., 2023).

Beyond improving academic outcomes, the integration of AI in science education has significant implications for sustainable development. Modern educational frameworks emphasize the development of sustainability competencies, including systems thinking, critical analysis, collaboration, and strategic problem-solving. AI-enabled learning environments have been shown to support these competencies by allowing students to explore real-world problems, simulate environmental and societal scenarios, and develop innovative solutions (Alkhawaja et al., 2025; Saseendran & Thomas, 2025). This aligns with global efforts to achieve Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure), which advocate for inclusive, equitable, and technologically enhanced learning systems.

However, despite the promising potential of AI, its integration into Nigerian secondary school science education is fraught with significant challenges. Empirical studies consistently highlight infrastructural deficiencies, including unreliable electricity supply, limited internet connectivity, and inadequate access to digital devices, as major barriers to implementation (Ahmed & Amao, 2025; Okunade, 2024). Additionally, there exists a substantial digital literacy gap among teachers, many of whom lack the training and confidence required to effectively utilize AI tools in classroom instruction (Waninga et al., 2025). These challenges not only hinder the adoption of innovative teaching approaches but also exacerbate existing educational inequalities between urban and rural schools.

Objectives of the Study

The study was designed to achieve the following objectives:

- To examine the effect of Artificial Intelligence (AI)-based instructional tools on students' engagement, motivation, and participation in STEM and Integrated Science learning in Nigerian secondary schools.
- To determine the effect of AI-driven instruction on students' conceptual understanding, academic performance, and acquisition of sustainable development skills in Integrated Science.

Research Questions

The study sought to provide answers to the following questions:

- To what extent does AI-based instruction influence students' engagement, motivation, and participation in STEM and Integrated Science classrooms?
- How does AI-driven instruction affect students' conceptual understanding, academic performance, and acquisition of sustainable development skills in Integrated Science?

1.1. Research Hypotheses

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

- **Ho_1:** AI-based instructional tools do not significantly influence students' engagement, motivation, and participation in STEM and Integrated Science learning.
- **Ho_2:** AI-driven instruction does not significantly affect students' conceptual understanding, academic performance, and acquisition of sustainable development skills in Integrated Science.

2. Methodology

This study adopted a quasi-experimental research design to investigate the effect of Artificial Intelligence (AI)-based instructional tools on students' engagement, motivation, conceptual understanding, academic performance, and acquisition of sustainable development skills in STEM and Integrated Science education. The design incorporated a pre-test and post-test control group structure, which enabled the researcher to examine causal relationships between AI-based instructional interventions and students' learning outcomes in real classroom settings where complete randomization was not feasible.

The population of the study comprised all junior secondary school students (JSS1–JSS3) in public secondary schools in Ikere Local Government Area of Ekiti State, Nigeria, where Basic Science serves as the foundation for STEM and Integrated Science learning. From this population, a sample of 180 students was selected from three purposively chosen public secondary schools that possessed basic computer and internet facilities necessary for implementing AI-based instruction and students were randomly assigned to experimental and control groups to ensure comparability and reduce selection bias.

The experimental group was exposed to AI-based instructional strategies, including the use of virtual laboratories, intelligent tutoring systems, and adaptive learning platforms designed to support personalized and interactive learning. These tools provided real-time feedback, enabled simulation of scientific concepts, and facilitated collaborative problem-solving activities. In contrast, the control group was taught using conventional teacher-centered instructional methods, characterized by lecture-based delivery and limited use of digital resources. The intervention was implemented over a defined instructional period, during which both groups were taught the same curriculum content to ensure consistency.

Data for the study were collected using achievement tests and structured engagement measures, administered as pre-tests and post-tests. The instruments were designed to assess students' levels of engagement, motivation, participation, conceptual understanding, academic performance, and acquisition of sustainable development skills. Content validity of the instruments was ensured through expert review, while reliability was established using appropriate statistical techniques prior to administration.

Descriptive statistics, including means and standard deviations, were used to summarize students' performance and engagement levels. To test the hypotheses, independent samples t-tests were employed to compare post-test scores between experimental and control groups, while paired samples t-tests were used to examine changes within groups from pre-test to post-test. All hypotheses were tested at a 0.05 level of significance, and effect sizes were calculated to determine the magnitude of the impact of AI-based instruction on students' learning outcomes.

3. Results

Table 1 Pre-test and Post-test Mean Scores of Students' Engagement and Motivation

Group	N	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD	Mean Diff
Experimental	90	45.32	6.41	78.56	5.88	33.24
Control	90	44.87	6.57	52.11	6.02	7.24

The results indicate that both the experimental and control groups had comparable pre-test mean scores, suggesting initial equivalence in engagement and motivation levels. However, after the intervention, the experimental group recorded a markedly higher post-test mean and mean difference compared to the control group. This suggests that AI-

based instructional tools substantially improved students' engagement and motivation in STEM and Integrated Science learning.

Table 2 Independent Samples t-test of Post-test Scores on Engagement and Motivation

Variable	Group	N	Mean	SD	t-value	df	p-value
Engagement & Motivation	Experimental	90	78.56	5.88			
	Control	90	52.11	6.02	29.84	178	0.000*

*Significant at $p < 0.05$

The table shows a statistically significant difference between the experimental and control groups in terms of engagement and motivation ($t = 29.84$, $p < 0.05$). This indicates that the observed improvement in the experimental group is not due to chance but as a result of the AI-based instructional intervention. Therefore, the null hypothesis (Ho_1) is rejected.

Table 3 Pre-test and Post-test Mean Scores of Conceptual Understanding and Academic Performance

Group	N	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD	Mean Diff
Experimental	90	42.37	7.02	81.23	7.15	38.86
Control	90	41.95	6.88	63.45	6.88	21.50

Similarly, Table 3 shows that students in the experimental group achieved a higher mean difference (38.86) compared to the control group (21.50), indicating improved conceptual understanding and academic performance.

Table 4 Independent Samples t-test of Post-test Scores on Conceptual Understanding and Academic Performance

Variable	Group	N	Mean	SD	t-value	df	p-value
Conceptual Understanding & Achievement	Experimental	90	81.23	7.15			
	Control	90	63.45	6.88	17.36	178	0.000*

*Significant at $p < 0.05$

Table 4 further confirms that the difference in performance between both groups is statistically significant ($t = 17.36$, $p < 0.05$). This implies that AI-based instruction significantly enhances students' conceptual understanding and academic achievement. Hence, Ho_2 is rejected.

4. Discussion of Findings

The findings of this study provide strong empirical support for the effectiveness of Artificial Intelligence (AI) in transforming STEM and Integrated Science education in Nigerian secondary schools. The discussion is presented in line with the major findings as reflected in the results tables.

The results presented in Table 1 and Table 2 indicate that students exposed to AI-based instructional tools demonstrated significantly higher levels of engagement, motivation, and participation compared to their counterparts in the control group. The substantial mean difference recorded by the experimental group, alongside the statistically significant difference observed in the t-test results, confirms that AI integration plays a critical role in enhancing students' classroom experiences.

This finding is consistent with the study by Okunade (2024), which reported that AI-driven instructional tools, particularly adaptive learning systems and intelligent tutoring platforms, significantly improve students' attention, curiosity, and active participation in science learning. Similarly, Ahmed and Amao (2025) found that AI-supported learning environments promote collaborative engagement and increase students' interest in STEM subjects by transforming the traditional "chalk-and-talk" approach into an interactive and learner-centered process. The ability of AI systems to provide real-time feedback and personalized learning pathways ensure that students remain actively involved in the learning process, thereby sustaining motivation.

From a theoretical standpoint, this outcome strongly supports the principles of constructivist learning theory, which emphasize that meaningful learning occurs when students actively engage with content rather than passively receiving information. AI tools facilitate such engagement by enabling learners to explore, experiment, and interact with scientific concepts in dynamic ways. In addition, the findings align with global perspectives that position AI as a key driver of innovation in education, capable of creating inclusive and engaging learning environments that cater to diverse learners (Ramli & Mahmud, 2025).

Furthermore, the results presented in Table 3 and Table 4 reveal that AI-based instruction significantly improved students' conceptual understanding and academic performance in Integrated Science. The experimental group recorded a markedly higher post-test mean and mean difference compared to the control group, and the t-test results confirmed that this difference is statistically significant. This indicates that AI tools are highly effective in simplifying complex scientific concepts and promoting deeper understanding.

This finding corroborates the work of Zhai et al. (2022), who demonstrated that machine learning applications can effectively support the assessment and development of students' scientific reasoning by providing immediate, data-driven feedback. The use of AI-driven simulations and virtual laboratories allows students to visualize abstract scientific processes, manipulate variables, and observe outcomes in real time, thereby enhancing comprehension and retention. Similarly, Okunade (2024) emphasized that AI-based instructional strategies improve students' mastery of difficult concepts in physics and chemistry through interactive and immersive learning experiences.

The improvement in students' academic performance can also be explained through cognitive load theory, which suggests that learners achieve better outcomes when complex information is presented in structured and manageable formats. AI tools reduce cognitive overload by breaking down complex concepts into interactive and visually rich representations, thereby facilitating understanding. Moreover, the findings indicate that AI-based instruction supports the development of higher-order thinking skills, including analysis, evaluation, and problem-solving, which are essential components of STEM education.

Importantly, beyond academic achievement, the findings suggest that AI integration contributes to the development of sustainable development competencies, such as critical thinking, collaboration, and systems thinking. These competencies are crucial for preparing students to address real-world challenges related to environmental sustainability, technological innovation, and socio-economic development. This aligns with the findings of Alkhawaja et al. (2025), who highlighted the role of AI in fostering skills necessary for achieving global sustainability goals through education.

However, while the benefits of AI integration are evident, the findings must be considered in light of existing contextual challenges. Previous studies have identified infrastructural limitations, including unreliable electricity supply, high internet costs, and inadequate access to digital tools, as major barriers to effective implementation (Ahmed & Amao, 2025; Waninga et al., 2025). In addition, the digital literacy gap among teachers remains a significant constraint, as the successful adoption of AI in education depends largely on educators' ability to integrate these technologies into their instructional practices. These challenges highlight the need for strategic investment in infrastructure, as well as continuous professional development for teachers.

Overall, the discussion demonstrates that AI is not merely an instructional aid but a transformational tool capable of redefining science education. By enhancing engagement, improving conceptual understanding, and fostering sustainability-oriented skills, AI provides a pathway for aligning STEM and Integrated Science education with the demands of a rapidly evolving, technology-driven global society.

5. Conclusion

The findings of this study clearly demonstrate that Artificial Intelligence (AI) can significantly enhance STEM and Integrated Science education in Nigerian secondary schools. AI-driven tools, including virtual laboratories, intelligent tutoring systems, and adaptive learning platforms, not only improve students' engagement and motivation but also strengthen their conceptual understanding and academic performance. Furthermore, the integration of AI fosters essential competencies aligned with sustainable development, such as problem-solving, collaboration, and systems thinking.

These results confirm that AI is not merely an instructional support but a transformative force capable of aligning science education with global sustainability objectives. By providing personalized, interactive, and learner-centered

experiences, AI enables students to acquire skills necessary for addressing real-world challenges and contributing meaningfully to the achievement of Sustainable Development Goals (SDGs).

Recommendations

Policymakers and school administrators should prioritize investment in digital infrastructure to ensure equitable access to AI tools across all secondary schools.

Teachers should receive continuous professional development to build competence in AI integration and instructional design.

Future research should explore longitudinal impacts of AI integration on students' STEAM competencies and sustainability-oriented problem-solving skills.

In conclusion, leveraging AI in science education presents a promising pathway for transforming STEAM learning, equipping students with the knowledge, skills, and attitudes needed for global sustainability. This aligns directly with the conference theme, emphasizing the critical role of scientific research and technological innovation in preparing students for the challenges of a rapidly evolving world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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