Emerging Trends and Challenges in the Use of Artificial Intelligence for Teaching Abstract Concepts in Science Education

Dr. Asiya Aliyu Ibrahim
Department of Educational Foundations,
Yusuf Maitama Sule Federal University of Education, Kano
aseealeeu@gmail.com
Rahina Umar Zandam
Department of General Studies Education
nabilazandam73@gmail.com

Abstract
*Artificial Intelligence (AI) is increasingly shaping science education, particularly in areas requiring visualization and conceptual modeling. This experimental study examined emerging trends and challenges associated with using AI-driven teaching systems to teach abstract science concepts in Nigerian secondary schools. A total of 180 science teachers from 12 public secondary schools were randomly assigned to an AI-supported instruction group ($n = 90$) or a traditional instruction group ($n = 90$). Over eight weeks, teachers in the experimental group used an AI-powered adaptive teaching platform to deliver lessons on abstract topics such as atomic structure, energy transformation, and cell processes. Student conceptual understanding and teacher instructional efficacy were measured pre- and post-intervention. Results revealed significant improvements in student understanding in the AI group ($p < .001$) and enhanced teacher instructional confidence. However, challenges related to infrastructure, digital literacy, and ethical concerns were reported. Findings highlight both the pedagogical potential and implementation barriers of AI in science edu*cation.

Keywords: Abstract, Adaptive, Artificial,, Concepts, Intelligence

Introduction

Teaching abstract scientific concepts has long been one of the most persistent challenges in science education. Topics such as atomic interactions, electromagnetic fields, and cellular metabolism involve processes that cannot be directly observed. Students often struggle to move beyond memorization toward meaningful understanding. Traditional teaching approaches, which rely heavily on verbal explanations and static diagrams, frequently fail to bridge this gap.

Artificial Intelligence (AI) is now emerging as a transformative force in education. AI-driven systems can personalize instruction, provide real-time feedback, and simulate complex processes through interactive environments. In science education, these capabilities are especially valuable because they allow learners to visualize invisible phenomena and engage with models dynamically rather than passively. Globally, AI applications in classrooms have expanded rapidly. Intelligent tutoring systems, adaptive learning platforms, and AI-powered simulations are being integrated into science curricula to enhance engagement and understanding. These tools can analyze learner responses, adjust difficulty levels, and provide targeted support, potentially improving conceptual learning outcomes (Fadel *et al.*, 2019).

In Nigeria, however, AI integration in secondary education is still at an early stage. While digital tools such as projectors and e-learning platforms have gained some ground, advanced AI-driven systems remain uncommon. Many schools face infrastructural challenges, including inconsistent power supply and limited internet access. Despite these constraints, interest in AI for education is growing, driven by national digital transformation initiatives.

This study explores how AI can be used specifically to teach abstract science concepts in Nigerian secondary schools. It focuses not only on learning outcomes but also on practical challenges faced by teachers implementing AI tools in real classrooms.

Research Questions

1. What effect does the use of AI-driven teaching systems have on secondary school students' conceptual understanding of abstract science concepts compared to traditional instruction?

Research Hypothesis

1. There is no significant difference in students' learning gains between those taught using AI-supported instruction and those taught using conventional teaching methods?

Literature Review

Emerging Trends in AI for Science Education

Artificial Intelligence is reshaping science education through a steady shift from uniform instruction toward adaptive, learner-centered environments. One of the most significant trends is the rise of intelligent tutoring and adaptive learning platforms that analyze student responses in real time and adjust content difficulty, pacing, and feedback accordingly. These systems rely on learning analytics and machine learning models to identify patterns in student performance, enabling personalized learning pathways that are especially useful when teaching abstract scientific ideas that require repeated exposure and scaffolded explanation (Holmes et al., 2023). In contrast to traditional whole-class instruction, AI-supported systems allow students to revisit challenging concepts such as atomic structure or thermodynamic processes until mastery is achieved.

Another growing trend is the use of AI-powered simulations and modeling tools in science classrooms. Abstract scientific phenomena often involve processes that are invisible to the naked eye or occur at scales beyond direct observation. AI-enhanced simulations help bridge this gap by dynamically representing processes such as molecular bonding, chemical reactions, genetic inheritance, or planetary motion (Mustafa *et al*., 2024). These tools allow learners to manipulate variables and immediately observe outcomes, which strengthens causal reasoning and systems thinking. Research increasingly shows that such interactive environments improve conceptual depth compared to static textbook diagrams.

AI chatbots and virtual assistants are also becoming part of science learning ecosystems. These conversational agents can provide instant explanations, answer follow-up questions, and guide students through problem-solving steps outside formal classroom hours. Their value lies in offering low-pressure academic support that encourages students to ask questions they might hesitate to raise in class. Studies suggest that AI assistants help reduce misconceptions by providing timely clarification, especially during independent practice or homework (Zawacki-Richter et al., 2022). Over time, these tools are evolving from simple question-answer systems to more pedagogically aware agents capable of guiding inquiry and prompting metacognitive reflection.

Assessment practices in science education are also being transformed by AI. Intelligent assessment systems now analyze not only final answers but also solution steps, response time, and patterns of errors. This enables formative feedback that is more diagnostic than traditional marking. For instance, if a learner repeatedly confuses mass and weight, the system can identify the conceptual misunderstanding and assign targeted remediation tasks. Such automated yet individualized feedback supports continuous monitoring of learning progress and allows teachers to focus their attention where it is most needed.

A further emerging direction involves the combination of AI with immersive technologies such as virtual reality and augmented reality. AI enhances these environments by adapting scenarios based on learner interaction and providing contextual prompts during exploration. Students can virtually enter a human cell, explore the solar system, or manipulate electromagnetic fields in three-dimensional space. These experiences support spatial reasoning and embodied cognition, which are critical for grasping abstract scientific ideas. Early evidence indicates that AI-driven immersive learning can improve engagement, long-term retention, and transfer of knowledge to new problem contexts.

AI and Conceptual Understanding of Abstract Science Concepts

Understanding abstract scientific concepts requires learners to mentally represent processes that cannot be directly observed, such as electron movement, energy transfer, or molecular interactions. AI systems support this cognitive process by linking symbolic representations, such as formulas and graphs, with dynamic visualizations and simulations. Instead of memorizing equations in isolation, students see how changes in variables affect outcomes in real time. This multimodal representation strengthens connections between conceptual, visual, and mathematical understanding, which is crucial for subjects like physics, chemistry, and biology (Luckin *et al*., 2024).

AI-supported modeling environments also promote active learning. Rather than passively receiving information, students test hypotheses, manipulate variables, and observe consequences within simulated systems. This inquiry-based approach aligns with constructivist learning theory, which holds that knowledge is built through interaction and reflection. When learners experiment with virtual circuits or ecological systems, they engage in scientific reasoning processes similar to those used by professional scientists. AI enhances this process by guiding exploration, offering hints, and adjusting task complexity based on learner performance.

Another important contribution of AI lies in its ability to detect and address misconceptions. Misconceptions in science are often persistent and resistant to traditional instruction. AI systems can analyze response patterns across multiple tasks to identify conceptual errors that may not be obvious from a single test. For example, if a student consistently misinterprets the direction of heat flow, the system can infer a flawed mental model and provide targeted explanations, alternative representations, and additional practice. This form of responsive remediation is difficult to achieve in large classrooms where teachers must divide attention among many learners.

Personalization further enhances conceptual understanding by aligning instruction with individual cognitive readiness. Some learners require concrete analogies before moving to symbolic representations, while others benefit from mathematical formalization earlier in the process. Adaptive AI platforms can adjust instructional sequences accordingly, ensuring that each learner progresses through conceptual stages at an appropriate pace. This flexibility is particularly valuable for abstract topics such as quantum phenomena or genetic probability, which often overwhelm students when presented too quickly or uniformly.

Finally, AI tools support metacognition, which plays a critical role in mastering abstract ideas. Many intelligent systems prompt learners to explain their reasoning, predict outcomes before running simulations, or reflect on errors after completing tasks. These prompts encourage students to think about their own thinking, strengthening self-regulated learning skills. Over time, this metacognitive scaffolding helps learners move beyond surface-level memorization toward deeper conceptual understanding and the ability to transfer knowledge to new scientific contexts.

Challenges of AI Integration in Developing Contexts

Despite the educational promise of AI, its integration in developing contexts faces significant structural barriers. In many regions, schools struggle with unreliable electricity, limited internet connectivity, and insufficient access to digital devices. AI systems often require stable infrastructure, regular updates, and technical maintenance, all of which can be difficult to sustain in under-resourced educational settings (UNESCO, 2023). Without foundational technological support, even the most advanced AI tools remain inaccessible or inconsistently used.

Teacher preparedness is another major challenge. Effective use of AI in science education requires not only technical skills but also pedagogical understanding of how to integrate digital tools meaningfully into lessons. Many teachers have limited exposure to AI technologies during their training and may feel uncertain about how to interpret AI-generated feedback or manage AI-supported activities. This skills gap can lead to superficial use, where technology is present but does not significantly enhance conceptual learning (Su, et al., 2025). Continuous professional development is therefore essential, yet often underfunded.

Financial constraints further limit adoption. AI platforms, subscriptions, hardware, and maintenance costs can be prohibitive for schools operating with tight budgets. Even when pilot programs introduce AI tools, sustainability becomes a concern once external funding ends. This creates inequities between well-resourced urban schools and rural or low-income schools, widening the digital divide rather than narrowing it. Policymakers must therefore consider long-term funding models and scalable solutions tailored to local realities. Ethical and governance concerns also pose challenges. AI systems rely on large amounts of student data to function effectively, raising questions about privacy, data security, and informed consent. In contexts where data protection policies are weak or poorly enforced, the risk of misuse increases. Algorithmic bias is another issue, as AI models trained on data from different educational or cultural settings may not accurately reflect local learning patterns, potentially leading to unfair or misleading assessments.

Finally, there are pedagogical and psychological concerns among educators. Some teachers worry that AI may reduce their professional autonomy or replace their role in the classroom. Others fear that over-reliance on automated systems could weaken human interaction, which is vital for motivation, emotional support, and social learning. Addressing these concerns requires framing AI as a supportive tool rather than a substitute for teachers. Successful integration depends on maintaining a balance where technology enhances instruction while teachers remain central to the learning process.

Methodology

This study adopted a randomized experimental research design using a pre-test and post-test control group structure. The design was selected to allow for a rigorous comparison of outcomes between participants exposed to AI-supported instruction and those who continued with conventional teaching practices. Random assignment helped reduce selection bias and strengthened the internal validity of the study by ensuring that differences observed after the intervention could be more confidently attributed to the treatment rather than pre-existing group differences.

The study involved 180 secondary school science teachers drawn from 12 public secondary schools in Kano State, Nigeria. Schools were selected to reflect a mix of urban and semi-urban settings to improve representativeness. Within the selected schools, participating teachers were randomly assigned to one of two groups: the experimental group (n = 90) and the control group (n = 90). Randomization was conducted using a simple random allocation procedure to ensure that each participant had an equal chance of being placed in either group.

Two major instruments were used for data collection. The first was the Student Conceptual Understanding Test (SCUT), a 40-item multiple-choice assessment designed to measure students' grasp of abstract scientific concepts taught by the participating teachers. Although teachers were the direct participants in the intervention, student performance was used as an indicator of instructional effectiveness. The second instrument was the Teacher AI Instructional Efficacy Scale (TAIIES), a 20-item Likert-type questionnaire developed to measure teachers' confidence and perceived competence in integrating AI tools into science instruction. The scales ranged from strongly disagree to strongly agree and covered areas such as instructional planning, use of AI feedback, and facilitation of inquiry using digital tools.

The instruments undergo validation through expert review in science education and educational technology. Reliability testing was conducted using Cronbach's alpha. The SCUT yielded a reliability coefficient of $\alpha = .88$, indicating high internal consistency, while the TAIIES recorded $\alpha = .91$, suggesting excellent reliability. These values show that both instruments were sufficiently stable and consistent for research purposes.

The experimental group participated in an eight-week instructional intervention during which teachers used an AI-powered adaptive teaching system designed to support the teaching of abstract science concepts. The system provided real-time analytics, adaptive content suggestions, automated formative feedback, and interactive simulations that teachers incorporated into their lessons. Teachers received initial orientation on how to use the system but implemented it within their normal classroom schedules. Meanwhile, teachers in the control group continued using traditional instructional methods, including textbook-based explanations, board illustrations, and standard laboratory demonstrations, without AI support.

Data collection occurred at two points. A pre-test was administered before the intervention to establish baseline equivalence between groups, and a post-test was conducted at the end of the eight-week period to measure changes in outcomes. For data analysis, independent samples t-tests were used to compare the mean scores of the experimental and control groups on both student conceptual understanding and teacher instructional efficacy. In addition, effect size statistics (Cohen's d) were calculated to determine the magnitude of the differences observed, providing a clearer interpretation of the practical significance of the findings beyond statistical significance.

Results

Research Question 1: What effect does the use of AI-driven teaching systems have on secondary school students' conceptual understanding of abstract science concepts compared to traditional instruction?
To answer this question, post-test scores from the Student Conceptual Understanding Test (SCUT) were compared between students taught by teachers in the AI-supported group and those taught by teachers in the control group.

Table 1: Post-Test Mean Scores of Students' Conceptual Understanding

Group	N	Mean Score	Standard Deviation
AI-Supported Instruction	90	31.84	4.12
Traditional Instruction	90	25.67	4.58

An independent samples t-test was conducted to determine whether the difference in mean scores between the two groups was statistically significant. $t(178) = 9.37$, $p < .001$. The result shows that students taught by teachers who used AI-driven instructional systems achieved a substantially higher mean score ($M = 31.84$) compared to those taught using traditional methods ($M = 25.67$). The difference of 6.17 points on a 40-item conceptual test indicates a meaningful improvement in understanding of abstract science concepts. The obtained t-value of 9.37 with a probability value less than .001 indicates that the difference between the two groups is statistically significant. This means the likelihood that this difference occurred by chance is extremely low. Therefore, the findings provide strong evidence that AI-supported teaching had a positive effect on students' conceptual understanding.

To further understand the magnitude of this effect, Cohen's d was calculated. Cohen's $d = 1.42$. This represents a very large effect size, suggesting that the average student in the AI-supported group outperformed approximately 92% of students in the traditional instruction group. Educationally, this implies

that AI-driven systems did not just produce minor improvements but led to substantial gains in students' grasp of complex and abstract scientific ideas.
Research Hypothesis 1: There is no significant difference in students' learning gains between those taught using AI-supported instruction and those taught using conventional teaching methods.

Learning gains were determined by subtracting pre-test scores from post-test scores for each group.

Table 2: Comparison of Students' Learning Gains

Group	N	Mean Gain Score	Standard Deviation
AI-Supported Instruction	90	9.12	3.21
Traditional Instruction	90	4.03	2.88

An independent samples t-test was conducted on the gain scores.

T (178) = 11.02, $p < .001$

The AI-supported group recorded a mean learning gain of 9.12 points, more than double the gain observed in the traditional instruction group (4.03 points). This indicates that students exposed to AI-enhanced teaching improved significantly more over the eight-week period than those in conventional classrooms. The calculated t-value of 11.02 and a p-value below .001 confirm that this difference in learning gains is statistically significant. Thus, the improvement in the AI group cannot be attributed to normal classroom progress alone; rather, it suggests that the AI intervention played a decisive role in accelerating conceptual learning. The effect size for learning gains was also computed: Cohen's d = 1.64

This is considered an extremely large effect size, demonstrating that AI-supported instruction had a powerful impact on students' academic growth. In practical classroom terms, this means that integrating AI tools into science teaching can dramatically enhance students' ability to understand and retain abstract scientific concepts within a relatively short instructional period.

Discussion of Findings

This study set out to examine the effects of AI-driven teaching systems on students' conceptual understanding of abstract science concepts and their overall learning gains. The statistical results provide compelling evidence that AI-supported instruction significantly enhanced learning outcomes when compared with traditional teaching methods.

The first key finding showed a statistically significant difference in post-test conceptual understanding scores between students exposed to AI-supported instruction and those taught using conventional methods, $t(178) = 9.37$, $p < .001$. Students in the AI group achieved a higher mean score ($M = 31.84$) than their counterparts in the control group ($M = 25.67$). The calculated effect size (Cohen's $d = 1.42$) indicates a very large educational impact. This suggests that AI-driven instructional systems substantially improved students' grasp of abstract scientific ideas, rather than producing only marginal benefits. This result aligns with findings reported by Holmes et al. (2023), who observed that AI-supported learning environments enhance conceptual understanding by providing interactive visualizations and adaptive feedback. Their study emphasized that when students engage with dynamic representations of scientific processes, they are more likely to develop accurate mental models. Similarly, the present study's large effect size suggests that AI simulations and real-time feedback helped learners connect theoretical explanations with visual and interactive experiences. The finding is also consistent with Luckin et al. (2024), who noted that AI-based educational tools support deeper cognitive processing by reducing extraneous cognitive load. In the current study, the higher performance of the AI group may be attributed to the system's ability to present complex information in manageable and visually rich formats, making abstract concepts easier to understand. The statistical strength of the result reinforces the view that AI tools can meaningfully enhance science instruction.

The second major finding revealed that students in the AI-supported group experienced significantly greater learning gains than those in the control group, $t(178) = 11.02$, $p < .001$. The mean gain score for the AI group ($M = 9.12$) was more than twice that of the traditional group ($M = 4.03$). The effect size for this difference, Cohen's $d = 1.64$, is considered extremely large, indicating that the AI intervention had a powerful influence on the rate and depth of learning over the eight-week period. This finding supports the argument that AI systems accelerate learning by providing personalized instructional pathways. Zawacki-Richter et al. (2022) reported similar outcomes, noting that AI-driven adaptive systems help identify learner misconceptions early and provide targeted support, leading to faster academic progress. The present study's statistical results echo this conclusion, suggesting that the AI platform's responsiveness to student needs contributed to the significantly higher learning gains observed. Furthermore, the magnitude of improvement observed in this study corresponds with Chen et al. (2020), who found that AI-supported instruction significantly increased students' mastery of complex science topics compared to traditional lecture-based teaching. Their work emphasized that immediate feedback and interactive engagement were key factors in promoting sustained learning improvements. The large effect size recorded here provides further empirical backing for those claims, particularly within the context of secondary science education.

Conclusion

AI presents powerful opportunities for enhancing science education, particularly for abstract topics. However, successful implementation requires infrastructure support, teacher training, and ethical safeguards. The statistical results demonstrate that AI-supported instruction significantly improved both students' conceptual understanding and their learning gains. These findings are consistent with prior international studies that highlight the effectiveness of AI in promoting deeper learning and personalized instruction. The large effect sizes observed suggest that AI has the potential to substantially enhance science education when implemented thoughtfully and supported by teacher training. This study therefore adds to the growing body of evidence that AI technologies can serve as powerful tools for improving the teaching and learning of abstract scientific concepts.

Recommendations

1. Educational stakeholders should consider the structured integration of AI-powered teaching systems into secondary school science curricula. The implementation should be gradual and guided by curriculum goals to ensure that technology enhances, rather than distracts from, learning objectives.

2. The school or government should organize training programs to help science teachers develop both technical competence and pedagogical strategies for integrating AI into their lessons.
3. Policymakers should also develop clear guidelines addressing data privacy, ethical use, and equitable access to AI technologies in education.

References

Chen, L., Chen, P., & Lin, Z. (2020). *Artificial intelligence in education: A review*. IEEE Access, 8, 75264–75278. Retrieved from https://doi.org/10.1109/ACCESS.2020.2988510

Fadel, C., Holmes, W., & Bialik, M. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning*. Boston, MA: Center for Curriculum Redesign.

Holmes, W., Bialik, M., & Fadel, C. (2023). *Artificial intelligence in education*. Routledge.

Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence unleashed: An argument for AI in education*. Pearson.

Mustafa, M. Y., Tlili, A., Lampropoulos, G., et al. (2024). *A systematic review of literature reviews on artificial intelligence in education (AIED): A roadmap to a future research agenda*. Smart Learning Environments, 11, Article 59. https://doi.org/10.1186/s40561-024-00350-5

Su, D., Xu, Y., & Tong, X. (2025). *Artificial intelligence in university science education: A systematic review of trends, challenges, and opportunities for learning outcomes*. Lecture Notes in Education Psychology and Public Media, 105, 51–56.

UNESCO. (2023). *Guidance for generative AI in education and research*. UNESCO Publishing.

Zawacki-Richter, O., Bond, M., Marin, V., & Gouverneur, F. (2022). Systematic review of AI in higher and school education. *International Journal of Educational Technology in Higher Education, 19*(1), 1–29.