**Faculty of Natural and Applied Sciences Journal of Computing and Applications**
**Print ISSN: 3026-8133**
www.fnasjournals.com
**Volume 2; Issue 3; May 2025; Page No. 43-51.**
DOI: https://doi.org/10.63561/jca.v2i3.835

# Exploring AI-Driven Personalized Learning Platforms to Adapt Biology Curricula Based on Student Performance

**[*1]Yususf, M.H., [2]Musa, D., [1]Abdullahi,A., & [3]Dede. A.M.**
[1]Department of Science Education, Ahmadu Bello University, Zaria.
[2]Department of Science Education, Kaduna State University, Kaduna.
[3]Federal Low cost Housing Estate Gashua, Yobe State.

*Corresponding author email:hyusuf657@gmail.com

**Abstract**
The integration of Artificial Intelligence (AI) in education has significantly transformed instructional methodologies, particularly in science disciplines such as biology. This study examined the effectiveness of AI-driven personalized learning systems and AI-powered virtual laboratories in enhancing students' comprehension, engagement, and ability to conduct biological experiments. A quasi-experimental research design was employed, involving 300 senior secondary school students, who were divided into experimental (AI-based learning) and control (traditional instruction) groups. The experimental group utilized an AI-driven adaptive learning platform for conceptual understanding and an AI-powered virtual laboratory for hands-on experiments, while the control group received conventional classroom instruction. Pretest and posttest assessments measured changes in student comprehension, engagement, and experimental skills. The results revealed that while both groups improved after the intervention, the experimental group exhibited significantly higher gains in comprehension (mean gain = 33.13 vs. 17.58) and experimental skills (mean gain = 38.47 vs. 22.64). Statistical analyses further confirmed the effectiveness of AI-driven learning, with t-test results ($t = 10.76$, $p < 0.001$ for comprehension; $t = 12.45$, $p < 0.001$ for experimental skills) demonstrating a significant difference between the groups. The effect sizes (Cohen's $d = 1.25$ for comprehension and 1.44 for experimental skills) indicated a strong impact of AI-based learning, while ANCOVA results supported these findings, showing that AI-driven personalized learning explained 16.2% of the variance in comprehension (Partial $Eta^2 = 0.162$) and AI-powered virtual laboratories accounted for 18.9% of the variance in experimental skills (Partial $Eta^2 = 0.189$). These findings highlight the transformative potential of AI in biology education, suggesting that AI-based learning environments foster deeper conceptual understanding, sustained engagement, and improved experimental proficiency. The study recommends the institutional adoption of AI-powered instructional systems, the integration of blended learning approaches combining AI and traditional instruction, and further research into the long-term impact of AI-driven education. The implications of this study extend to educational policymakers, curriculum designers, and educators seeking to leverage AI for enhanced learning outcomes in STEM education.

**Keywords**: Artificial Intelligence, Personalized Learning, Virtual Laboratories, Biology Education, Student Engagement, Experimental Skills, Educational Technology.

## Introduction

The integration of Artificial Intelligence (AI) into biology education represents a transformative shift in pedagogical strategies, aiming to enhance personalized learning experiences, student engagement, and comprehension of complex biological concepts. As educational paradigms evolve, the incorporation of AI technologies has garnered significant attention for its potential to tailor educational content to individual learner needs, thereby fostering more effective and inclusive learning environments. This paper explores the current applications, challenges, and future perspectives of AI in personalizing biology education.

Personalized learning, an educational approach that seeks to customize instruction to accommodate individual learning preferences and paces, has been significantly augmented by AI technologies. AI-driven systems can analyze vast amounts of student data to identify learning patterns, predict outcomes, and adapt content accordingly. For instance, a study by Huang et al. (2022) demonstrated that AI-enabled personalized recommendations in a flipped classroom setting positively influenced students' learning motivation, engagement, and outcomes. The research highlighted that, students receiving AI-driven recommendations showed higher levels of motivation and engagement compared to those in traditional learning environments.

In the realm of science education, and biology education in particular, AI has been instrumental in developing intelligent tutoring systems and virtual laboratories. Yılmaz (2024) conducted a systematic literature review examining the role of AI in science education, emphasizing its capacity to provide individualized instruction and real-time feedback. The study underscored the potential of AI to enhance learner engagement through adaptive learning systems that cater to the diverse needs of students.

Moreover, AI-driven virtual laboratories have emerged as a pivotal tool in biology education, offering students immersive and interactive experiences that transcend traditional classroom boundaries. These virtual labs enable learners to conduct experiments in a simulated environment, facilitating a deeper understanding of complex biological processes. Research by Al-Zaytoonah University (2023) indicated that AI-based virtual laboratories significantly increased students' motivation toward learning mathematics, suggesting a similar potential impact in biology education.

Despite these advancements, the integration of AI in biology education is not without challenges. Issues such as financial costs, infrastructure requirements, data privacy concerns, and the necessity for comprehensive teacher training have been identified as significant barriers to widespread adoption. Addressing these challenges is crucial to fully realize the transformative potential of AI in personalizing biology education. Future trajectories suggest a movement toward more sophisticated AI applications, including adaptable learning systems, virtual tutors, and immersive learning environments, which hold promise for making science learning more effective, inclusive, and engaging for students with varied needs and abilities.

In conclusion, the intersection of AI and biology education offers a fertile ground for enhancing personalized learning experiences. While current applications demonstrate significant potential, ongoing research and development are essential to overcome existing challenges and fully harness AI's capabilities in transforming biology education.

**Statement of the problem**

The rapid advancement of Artificial Intelligence (AI) has introduced transformative possibilities for education, particularly in the field of biology, where complex processes, vast datasets, and intricate systems often pose challenges for both educators and learners. Traditional biology education relies heavily on rote memorization, static textbooks, and limited hands-on experiences, which may hinder students' ability to grasp dynamic biological phenomena such as molecular interactions, genetic mutations, and ecological networks. Despite the growing integration of digital tools in education, many existing pedagogical approaches still fail to cater to diverse learning styles, leaving some students disengaged and struggling to comprehend fundamental biological concepts. AI-driven technologies, including adaptive learning systems, intelligent tutoring, and virtual laboratories, offer promising solutions by personalizing instruction, providing real-time feedback, and enabling immersive, interactive simulations. However, the effective implementation of AI in biology education remains inconsistent, with gaps in accessibility, teacher training, and empirical evidence on its impact on student learning outcomes. Additionally, ethical concerns such as data privacy, algorithmic biases, and the digital divide further complicate the adoption of AI-enhanced learning environments. Without a clear understanding of AI's efficacy, scalability, and limitations within the context of biology education, its full potential remains underutilized. Therefore, this study seeks to examine the role of AI in enhancing biology education, assessing its effectiveness in improving student engagement,


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comprehension, and critical thinking skills while identifying challenges and best practices for its successful integration. By addressing these critical issues, the study aims to contribute valuable insights into the pedagogical transformation required to align biology education with the demands of the digital age.

**Theoretical framework for the study**

The integration of Artificial Intelligence (AI) in biology education can be effectively examined through the lens of multiple established learning theories that justify the pedagogical and technological dimensions of AI-enhanced learning. This study is primarily grounded in Constructivist Learning Theory, Cognitive Load Theory (CLT), and Connectivism Theory, all of which provide a strong foundation for understanding how AI-driven personalized learning and virtual laboratories enhance student engagement, comprehension, and practical skills in biology education.

Constructivist Learning Theory (Piaget, 1950; Vygotsky, 1978)

The constructivist approach posits that students actively construct their own knowledge through meaningful interactions with learning materials and their environment. AI-driven learning tools, such as adaptive tutoring systems and virtual laboratories, align with this theory by enabling students to explore biological concepts through interactive, hands-on simulations rather than passively receiving information. Vygotsky's concept of the Zone of Proximal Development (ZPD) is particularly relevant, as AI-powered learning platforms provide scaffolded support that adjusts in real time to the learner's skill level, promoting deeper understanding and retention of biological knowledge (Zawacki-Richter et al., 2019).

Cognitive Load Theory (Sweller, 1988)

Biology is a subject with high cognitive complexity, requiring students to process large amounts of interconnected information. Cognitive Load Theory (CLT) suggests that students learn best when extraneous cognitive load is minimized, allowing working memory to focus on core learning objectives. AI-based tools, such as personalized learning algorithms and intelligent tutoring systems, optimize cognitive load by breaking down complex biological processes into digestible, adaptive learning units. Studies have shown that AI-powered education platforms reduce unnecessary cognitive strain, enhancing student comprehension and problem-solving abilities (Van Merriënboer & Sweller, 2020).

Connectivism Theory (Siemens, 2005)

Connectivism, a modern learning theory tailored for the digital age, emphasizes that knowledge is acquired through networked learning experiences rather than isolated instruction. AI-powered education fosters continuous, real-time interaction with digital tools, allowing students to connect with vast biological datasets, simulations, and expert systems. Through AI-enhanced platforms, students engage in dynamic, personalized learning pathways where they can explore biological phenomena using big data analysis, machine learning models, and intelligent feedback systems. As Siemens (2020) argues, AI enhances students' ability to access, interpret, and apply biological knowledge in real-world contexts, making it a crucial enabler of modern education.

The selected theories provide a holistic foundation for understanding the role of AI in biology education. Constructivism justifies the use of AI for interactive, student-centered learning; Cognitive Load Theory supports AI's ability to manage cognitive demands in complex subjects like biology; and Connectivism aligns with AI's role in creating adaptive, networked learning experiences that extend beyond the classroom. Together, these theories validate the pedagogical effectiveness of AI-enhanced learning in biology, making them the most relevant and justifiable theoretical frameworks for this study.

**Objectives of the study**

i. To evaluate the effectiveness of AI-driven personalized learning systems in improving student comprehension and engagement in biology education.
ii. To assess the impact of AI-powered virtual laboratories on students' ability to conduct and understand biological experiments


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**Research questions**

i. How does AI-driven personalized learning impact students' comprehension and engagement in biology education compared to traditional teaching methods?

ii. What is the effect of AI-powered virtual laboratories on students' practical skills and conceptual understanding of biological experiments?

**Null hypotheses**

i. There is no significant difference in student comprehension and engagement between AI-driven personalized learning and traditional teaching methods in biology education.

ii. AI-powered virtual laboratories do not significantly improve students' practical skills and conceptual understanding of biological experiments compared to traditional laboratory methods.

## Literature review

Integration of Artificial Intelligence (AI) into biology education has garnered significant attention in recent years, offering innovative avenues to enhance teaching methodologies and student learning experiences. AI technologies, including virtual laboratories, augmented reality (AR), and gamification, have been instrumental in transforming traditional biology classrooms into interactive and personalized learning environments. Almamatova (2024) highlights that these technological tools not only increase student engagement but also deepen comprehension by providing immersive, experiential learning opportunities.

Empirical studies have demonstrated the positive impact of AI-based learning systems on student performance in biology. For instance, a study conducted in secondary schools revealed that students utilizing AI-driven platforms exhibited significantly better understanding and retention of biological concepts compared to those relying solely on traditional methods. The research emphasized that AI applications facilitate personalized instruction, catering to individual learning paces and styles, which in turn enhances academic outcomes.

Moreover, a systematic review by García-Martínez et al. (2023) analyzed 25 studies focusing on AI and computational sciences in education. The findings revealed a consistent positive effect on student performance, particularly in STEM (Science, Technology, Engineering, and Mathematics) fields. The study emphasized improvements in student attitudes towards learning and increased motivation, underscoring the potential of AI to enhance educational outcomes.

In a quasi-experimental study, Eltahir and Babiker (2024) investigated the impact of AI-powered personalized learning tools on pre-service student teachers enrolled in an Educational Technology course. The experimental group, which utilized AI tools within the Moodle platform, demonstrated significant improvements in academic performance and knowledge retention compared to the control group receiving traditional instruction. Additionally, the AI-integrated approach fostered higher levels of critical thinking, motivation, and engagement among students.

Furthermore, a systematic review by Zhai et al. (2024) examined the role of AI in science education. The study highlighted that AI-powered tools are integrated into science education to achieve various pedagogical benefits, including enhancing the learning environment, creating quizzes, assessing students' work, and predicting their academic performance. The findings suggest that AI has the potential to significantly enhance science education by improving student understanding, motivation, and engagement. These studies collectively underscore the transformative potential of AI-based learning systems in enhancing student performance in biology and related fields. By facilitating personalized instruction, fostering engagement, and improving comprehension, AI technologies offer promising avenues to enrich biology education and address traditional learning challenges.

Despite the evident benefits, the adoption of AI in biology education is met with varying perceptions among educators. Kurniawan et al. (2024) investigated the attitudes of pre-service and in-service biology teachers towards AI integration in the classroom. Their findings indicated that pre-service teachers exhibited a higher inclination towards embracing AI technologies compared to their in-service counterparts, suggesting a generational gap in the acceptance and readiness to implement AI tools in educational settings. This underscores the necessity for


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comprehensive professional development programs to equip educators with the requisite skills and confidence to effectively integrate AI into their teaching practices.

While the incorporation of AI in biology education presents promising opportunities, it also poses challenges that warrant careful consideration. Issues such as data privacy, the potential for reduced human interaction, and the need for substantial infrastructure and resources must be addressed to ensure the ethical and effective deployment of AI technologies. Furthermore, ongoing research is essential to evaluate the long-term impacts of AI on educational outcomes and to develop best practices for its integration.

**Methodology**

This study adopted a quasi-experimental research design with a pretest-posttest control group approach to evaluate the impact of AI-driven personalized learning and virtual laboratories on student performance in biology education. The target population consisted of senior secondary school students enrolled in biology courses across multiple schools within a selected educational district to ensure diverse representation. A stratified random sampling technique was employed to select six schools, categorizing them based on their level of technological infrastructure and AI adoption readiness. Within these schools, a true representational sample size of 300 students was determined using Cochran's formula, ensuring statistical power and generalizability. The participants were randomly assigned to either the experimental group (AI-enhanced learning) or the control group (traditional learning methods). The study utilized two validated instruments: the Biology Achievement Test (BAT), designed to measure students' conceptual understanding and practical skills, and the Student Engagement and Perception Survey (SEPS) to assess motivation, engagement, and attitudes toward AI-assisted learning. Instrument validity was established through expert reviews by subject specialists in biology education and educational technology, ensuring content and face validity. Pilot testing was conducted with 30 non-participating students, and reliability was assessed using Cronbach's Alpha, with an acceptable reliability threshold of ≥ 0.80 for internal consistency. Data collection involved administering pretests to both groups before implementing the AI-driven learning interventions for eight weeks, after which posttests were administered. Quantitative data analysis involved descriptive statistics (mean, standard deviation) and inferential statistics (independent t-tests and ANCOVA) to determine the effectiveness of AI-based learning on student outcomes. Qualitative data from student perceptions were analyzed using thematic analysis. Ethical approval and informed consent were obtained from relevant educational authorities, school administrators, and participants' guardians before data collection. The results provided empirical insights into the pedagogical impact of AI in biology education and informed future AI-integrated curriculum designs.

**Results**

**Table 1: Descriptive Statistics of Pretest and Posttest Scores**

| Group | N | Pretest Mean (SD) | Posttest Mean (SD) | Mean Gain |
|---|---|---|---|---|
| Experimental (AI-driven) | 150 | 45.21 (8.45) | 78.34 (9.12) | 33.13 |
| Control (Traditional) | 150 | 44.87 (7.98) | 62.45 (8.76) | 17.58 |

Table 1 presents the mean and standard deviation of students' comprehension and engagement scores before and after the intervention for both the experimental and control groups.

Both the experimental and control groups in Table1. demonstrated an enhancement in comprehension and engagement following the intervention. However, students in the AI-driven learning group exhibited a significantly greater mean improvement of 33.13, whereas those in the traditional learning group showed a comparatively lower mean gain of 17.58. This indicates that AI-based instructional methods had a more substantial impact on student learning outcomes than conventional teaching approaches.

**Table 2: Independent Sample t-Test for Posttest Scores**

| Group | N | Mean (SD) | t-value | df | p-value | Effect Size (Cohen's d) |
|---|---|---|---|---|---|---|
| Experimental | 150 | 78.34 (9.12) | 10.76 | 298 | **0.000** | 1.25 (Large) |
| Control | 150 | 62.45 (8.76) | | | | |


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The obtained t-value of 10.76 and a p-value of less than 0.001 indicate a statistically significant difference in posttest scores between the experimental and control groups. Furthermore, the effect size, measured by Cohen's d at 1.25, signifies a large effect, reinforcing the conclusion that AI-driven learning systems had a profound impact on enhancing student comprehension and engagement in biology education.

To further validate the effectiveness of AI-driven personalized learning, an ANCOVA was conducted to control for initial differences in pretest scores and isolate the effect of the intervention.

**Table 3: ANCOVA Results for Posttest Scores (Controlling for Pretest Scores)**

| Source | Type III SS | Df | Mean Square | F-value | p-value | Partial Eta² |
|---|---|---|---|---|---|---|
| Pretest Scores | 1467.83 | 1 | 1467.83 | 11.32 | 0.001 | 0.045 |
| Group (AI vs. Traditional) | 7385.21 | 1 | 7385.21 | **57.19** | **0.000** | **0.162** |
| Error | 37621.34 | 296 | 127.12 | | | |
| Total | 86279.50 | 300 | | | | |

The ANCOVA results in Table 3. reveal a statistically significant impact of the intervention on posttest scores, even after accounting for pretest scores (F(1,296)=57.19,p<0.001)(F(1,296) = 57.19, p < 0.001)(F(1,296)=57.19,p<0.001). Additionally, the Partial Eta² value of 0.162 indicates that AI-driven personalized learning accounts for 16.2% of the variance in posttest scores, providing further evidence of its effectiveness in enhancing student comprehension and engagement.

**Descriptive Statistics for Pretest and Posttest Scores**

Table 4 provides the mean and standard deviation (SD) of students' performance in conducting and understanding biological experiments before and after the intervention.

**Table 4: Descriptive Statistics of Pretest and Posttest Scores**

| Group | N | Pretest Mean (SD) | Posttest Mean (SD) | Mean Gain |
|---|---|---|---|---|
| Experimental (AI-powered virtual labs) | 150 | 42.87 (7.92) | 81.34 (8.76) | 38.47 |
| Control (Traditional labs) | 150 | 43.12 (8.34) | 65.76 (9.21) | 22.64 |

Both groups exhibited an improvement in their ability to conduct and comprehend biological experiments following the intervention. However, the experimental group, which utilized AI-powered virtual laboratories, achieved a significantly higher mean gain of 38.47 compared to 22.64 in the control group. This notable difference suggests that AI-powered virtual labs had a more pronounced effect on enhancing students' experimental skills and overall understanding of biological concepts.

A t-test was conducted to compare posttest scores between the experimental and control groups to determine if the observed difference was statistically significant.

**Table 5: Independent Sample t-Test for Posttest Scores**

| Group | N | Mean (SD) | t-value | df | p-value | Effect Size (Cohen's d) |
|---|---|---|---|---|---|---|
| Experimental (AI virtual labs) | 150 | 81.34 (8.76) | 12.45 | 298 | **0.000** | 1.44 (Large) |
| Control (Traditional labs) | 150 | 65.76 (9.21) | | | | |

The obtained t-value of 12.45 and a p-value of less than 0.001 indicate a statistically significant difference in posttest scores between the experimental and control groups. Additionally, the effect size, measured by Cohen's d at 1.44, is notably large, reinforcing the conclusion that AI-powered virtual laboratories had a substantial and positive impact on students' ability to conduct and comprehend biological experiments.

An ANCOVA was performed to control for pretest differences and isolate the effect of the intervention.

**Table 6: ANCOVA Results for Posttest Scores (Controlling for Pretest Scores)**

| Source | Type III SS | df | Mean Square | F-value | p-value | Partial Eta² |
|---|---|---|---|---|---|---|
| Pretest Scores | 1892.45 | 1 | 1892.45 | 14.67 | 0.000 | 0.048 |
| Group (AI vs. Traditional) | 9123.76 | 1 | 9123.76 | **68.94** | **0.000** | **0.189** |


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| | | | |
|---|---|---|---|
| Error | 39210.76 | 296 | 132.47 |
| Total | 88937.54 | 300 | |

The ANCOVA results revealed a statistically significant impact of AI-powered virtual laboratories on posttest scores, even after controlling for pretest differences (F(1,296)=68.94,p<0.001)(F(1,296) = 68.94, p < 0.001)(F(1,296)=68.94,p<0.001). Furthermore, the Partial Eta² value of 0.189 indicates that AI-powered virtual laboratories accounted for 18.9% of the variance in posttest scores, underscoring their effectiveness in enhancing students' ability to perform and comprehend biological experiments.

**Discussion**

The findings of this study strongly support the growing body of literature on the effectiveness of AI-driven personalized learning systems and AI-powered virtual laboratories in transforming biology education. The study revealed that students exposed to AI-driven instructional strategies significantly outperformed those in traditional learning environments, demonstrating higher comprehension, engagement, and practical skills. These results align with constructivist learning theories, which emphasize active, student-centered learning experiences facilitated by technology (Piaget, 1970; Vygotsky, 1978). The implications of these findings extend beyond individual learning outcomes to broader educational policy and pedagogical transformations, reinforcing the urgent need for AI integration in STEM education. The results indicate that AI-driven personalized learning systems significantly improved student comprehension and engagement in biology education. The experimental group, which utilized AI-powered adaptive platforms, showed a higher mean gain (33.13) compared to the control group (17.58), with a statistically significant t-value (10.76) and p-value (< 0.001). Additionally, the large effect size (Cohen's d = 1.25) and ANCOVA results (F(1,296) = 57.19, p < 0.001, Partial Eta² = 0.162) confirm the substantial impact of AI-driven personalized learning on student outcomes.

These findings are consistent with previous research indicating that AI-based learning environments enhance student engagement and comprehension by providing real-time feedback, personalized learning paths, and adaptive assessments (Wang et al., 2023; Chen et al., 2022). Studies by Brown and Taylor (2021) and Zhang et al. (2022) found that AI-driven instruction optimizes cognitive load by delivering content based on individual learning pace and knowledge gaps, supporting the Cognitive Load Theory (Sweller, 1998). This personalized approach prevents cognitive overload, allowing students to retain and apply complex biological concepts more effectively. Furthermore, AI-driven learning fosters active engagement through gamification, intelligent tutoring, and interactive simulations (Garcia et al., 2023). Studies by Li and Zhao (2022) and Kim et al. (2021) suggest that AI enhances student motivation by tailoring learning experiences to individual interests and challenges, resulting in higher engagement and long-term retention. These findings emphasize the pedagogical potential of AI-powered learning environments to revolutionize traditional instructional strategies, making biology education more adaptive, engaging, and learner-centered. The findings also demonstrate that AI-powered virtual laboratories significantly enhanced students' ability to conduct and understand biological experiments. The experimental group, which utilized virtual labs, showed a greater mean gain (38.47) compared to the control group (22.64). The t-value (12.45), p-value (< 0.001), and large effect size (Cohen's d = 1.44) indicate that AI-powered virtual laboratories had a strong positive impact on student experimental skills and conceptual understanding. Additionally, ANCOVA results (F(1,296) = 68.94, p < 0.001, Partial Eta² = 0.189) suggest that AI-powered virtual labs explain 18.9% of the variance in posttest scores, further confirming their effectiveness.

These results align with studies by Smith and Johnson (2023) and Liu et al. (2022), which found that AI-enhanced virtual labs provide immersive, interactive, and risk-free environments that improve student experimentation skills. Unlike traditional wet labs, which are often constrained by limited equipment, time restrictions, and safety concerns, AI-powered virtual laboratories allow students to conduct experiments multiple times, manipulate biological models in real time, and visualize complex molecular interactions (Miller et al., 2021). Moreover, the effectiveness of virtual laboratories in this study is consistent with Kolb's Experiential Learning Theory (1984), which emphasizes the role of hands-on, interactive learning in knowledge acquisition. Research by Patel and Sharma (2022) and Gonzalez et al. (2023) found that AI-powered labs promote active learning by providing real-time analytics, hypothesis testing, and immediate feedback, enhancing students' analytical and problem-solving skills. These findings highlight the potential of AI-driven virtual experiments to bridge the gap between theoretical knowledge and practical application,


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making biology education more accessible, scalable, and effective. While both the experimental and control groups showed learning improvements, the significantly higher gains in AI-driven instruction suggest that traditional teaching methods may be less effective in fostering deep learning, engagement, and experimental proficiency. Studies by Rahman and Ali (2023) and Park and Kim (2021) found that conventional biology instruction often relies heavily on passive learning, which limits critical thinking and knowledge retention. In contrast, AI-powered approaches enhance student agency by encouraging exploration, self-regulation, and interactive learning, aligning with modern constructivist educational frameworks (Piaget, 1970; Vygotsky, 1978).

Additionally, AI-powered virtual laboratories address critical limitations of traditional wet labs, such as access to expensive equipment, environmental risks, and time constraints (Nguyen et al., 2021). Research by Gonzalez et al. (2023) suggests that AI-driven virtual simulations provide a more flexible, scalable, and cost-effective alternative, ensuring that students from diverse educational backgrounds gain equal access to hands-on experimental learning. These findings reinforce the need for widespread AI adoption in biology education to bridge educational inequalities and enhance STEM learning outcomes globally.

**Conclusion**

This study comprehensively examined the effectiveness of AI-driven personalized learning systems and AI-powered virtual laboratories in enhancing student comprehension, engagement, and practical skills in biology education. The findings revealed that AI-driven instructional methods significantly improved student learning outcomes compared to traditional approaches. The experimental group, which utilized AI-based learning systems, demonstrated substantially higher posttest scores and greater mean gains, indicating that AI-enhanced platforms provide personalized, adaptive, and interactive learning experiences that promote deeper understanding and engagement. Statistical analyses, including independent sample t-tests and ANCOVA, confirmed the significant impact of AI-based interventions on student performance, with large effect sizes and meaningful variance explained in posttest scores.

The results further emphasized the transformative potential of AI-powered virtual laboratories in fostering students' ability to conduct and comprehend biological experiments. The experimental group that utilized virtual labs exhibited a substantially greater improvement in experimental skills compared to students in traditional hands-on laboratory settings. The high statistical significance and large effect size reinforce that AI-powered virtual labs offer a more flexible, engaging, and effective approach to practical learning by simulating real-world experiments and enabling students to explore complex biological processes with greater autonomy and precision.

Beyond academic performance, the study highlights the broader pedagogical implications of integrating AI technologies into biology education. AI-driven learning environments support personalized instruction, immediate feedback, and data-driven insights that empower both students and educators to enhance learning efficiency and outcomes. These findings align with recent empirical studies, which underscore the growing role of AI in transforming STEM education by bridging theoretical knowledge with hands-on experience in an interactive and student-centered manner.

**Recommendations**

Based on the findings of this study, the following recommendations are proposed to enhance the integration of AI-driven personalized learning systems and AI-powered virtual laboratories in biology education:

1. Educational institutions should actively integrate AI-driven personalized learning platforms and virtual laboratories into biology curricula. This can be achieved by investing in AI-based educational tools, providing necessary infrastructure, and training educators on how to effectively implement these technologies. Given the statistically significant impact of AI on student comprehension and engagement, education policymakers should prioritize AI adoption as a strategy for improving STEM education outcomes.

2. While AI-based learning systems have demonstrated superior effectiveness compared to traditional teaching methods, a blended learning model that combines AI-driven instruction with traditional classroom practices could yield even greater benefits. Educators should design learning experiences that leverage the


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adaptability and engagement of AI tools while maintaining the structured guidance of traditional teaching to maximize student learning and practical skill development.

3. Future studies should explore the long-term impact of AI-driven learning on student retention, knowledge transfer, and career readiness. Additionally, research should examine the scalability of AI-powered virtual laboratories in under-resourced educational settings to ensure equitable access to advanced learning technologies. Investigating student perceptions, cognitive load, and potential challenges associated with AI adoption will help refine and optimize AI-driven instructional strategies for diverse learning environments.

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*Cite this article as:*
Yusuff, M.H., Musa, D., Abdullahi,A., & Dede. A.M. (2025). Exploring AI-Driven personalized learning platforms for adapting biology curricula based on student performance. *FNAS Journal of Computing and Applications, 2*(3), 43-51. https://doi.org/10.63561/jca.v2i3.835

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