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EFFECT OF AI-ENHANCED INSTRUCTION ON THE ACADEMIC PERFORMANCE AND SUSTAINABILITY MINDSET OF SENIOR SECONDARY SCHOOL STUDENTS IN BIOLOGY IN PORT HARCOURT METROPOLIS, RIVERS STATE, NIGERIA.

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ABSTRACT
This study investigated the effects of AI-enhanced instruction on academic performance and sustainability mindset of senior secondary school students in Biology in Port Harcourt Metropolis, Rivers State, Nigeria. A descriptive and quasi-experimental design was adopted. The population consisted of 45 public schools, with 16,363 SS2 students and 108 Biology teachers. A sample of 60 teachers, 4 schools, and 240 students was selected using purposive and stratified random sampling. Students were assigned to control (n = 120, taught with the discussion method) and experimental groups (n = 120, taught using AI-adaptive learning platforms and simulations that connected Biology concepts with sustainability challenges). Three research questions and hypotheses guided the study. Instruments included a validated questionnaire on AI in Biology teaching and a Biology Performance Test (BPT), both with a reliability coefficient of 0.80. Data were analyzed using means, standard deviations, the Z-test, and the F-test at a 0.05 significance level. Results revealed a significant difference in performance, favoring students taught with AI-enhanced instruction. Findings further showed that while AI supports sustainability awareness by linking Biology to real-life challenges, its classroom application is still limited. Both male and female Teachers reported inadequate exposure to AI tools in the classroom, hindering students' sustainability mindset development. Key challenges include limited teacher competence, poor digital infrastructure, and high costs. It was recommended that teachers receive AI-based training, ICT facilities be provided, and curricula be redesigned to integrate AI applications for academic and sustainability goals.

Keywords: Artificial Intelligence, Biology Education, Academic Performance, Sustainability Mindset,

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INTRODUCTION

Education is universally recognized as a vital driver of human development and societal progress. It equips learners with the knowledge, attitudes, and skills necessary to confront real-world challenges, while also preparing them to participate meaningfully in civic life. In the twenty-first century, the role of education extends beyond the acquisition of facts; it emphasizes creativity, innovation, and problem-solving capacities that enable learners to thrive in a knowledge-driven and sustainability-conscious world (UNESCO, 2021). Within this broad mandate, Science education has assumed a central position because of its ability to foster inquiry, critical thinking, and evidence-based reasoning. Among the science disciplines, Biology occupies a particularly important role because of its direct relevance to life, the environment, and sustainable living. It exposes learners to concepts that connect with everyday life: health, food security, ecology, and climate adaptation; thereby nurturing awareness of the interconnectedness between human activity and environmental well-being. Scholars have traced part of this problem to the dominance of conventional teaching methods in Nigerian classrooms, particularly lecture and discussion approaches (Okeke & Ugwu, 2022; Adeoye, 2023).

While these methods can transmit information, and encourage dialogue, they often fall short in stimulating deep learner engagement. Students frequently memorize content rather than develop meaningful understanding, which limits their ability to apply knowledge beyond the classroom (Eze & Nwosu, 2020). Lessons, therefore, remain largely teacher-centered, with minimal use of modern strategies that promote collaboration, critical thinking, and creativity. The discussion method, in particular, is widely practiced because of its interactive nature. It enables learners to share ideas, ask questions, and clarify misconceptions under teacher guidance (Adeoye, 2023). In Biology classrooms, it can help students relate abstract concepts such as ecology or pollution to real-life experiences, thereby enhancing reflection on sustainability issues like deforestation and climate change (Nwankwo & Okoro, 2021). Yet its weaknesses remain evident. Discussions are often dominated by outspoken students while others remain passive, and without structured facilitation, the depth of analysis is limited. This undermines the development of higher-order thinking and problem-solving skills necessary to address pressing environmental challenges (Eze & Nwosu, 2020). In contrast, Artificial Intelligence (AI) introduces a dynamic alternative through tools such as Intelligent Tutoring Systems, Adaptive Learning Platforms, Simulations, Chatbots, and Learning Analytics (Holmes et al., 2022).

Simulations and adaptive platforms, in particular, hold promise for Biology education, as they allow learners to conduct virtual experiments, visualize complex systems, and receive tailored feedback on topics like ecology, pollution, conservation, and waste management. Empirical evidence underscores this shift. Chen et al. (2021) found that students using AI simulations outperformed those taught with discussions, while Al-Ghamdi and Samarji (2022) reported improved mastery of genetics and environmental science. Yang and Chang (2020) and Adeyemo et al. (2023) further showed that AI fosters sustainability values, creativity, and ecological responsibility. Yet, challenges persist in Nigeria: poor infrastructure, inadequate training, and high costs hinder adoption (Okonkwo & Nwankwo, 2021; Bello & Ahmed, 2022). Central to this discourse is the development of a *sustainability mindset (SM)*, defined as the integration of knowledge, skills, values, and attitudes that empower learners to contribute to sustainable development and act responsibly toward environmental, social, and economic challenges (UNESCO, 2021; Wiek et al., 2011). A sustainability mindset transcends rote learning, enabling students to approach sustainability challenges with creativity and responsibility. Teachers play a

pivotal role in cultivating this mindset by leveraging AI-enhanced instruction to transform Biology classrooms into spaces of inquiry and problem-solving. Through adaptive learning platforms and simulations, teachers can guide students to connect biological principles with sustainability challenges, making abstract concepts concrete and relevant. In this way, teachers are not merely transmitters of knowledge but facilitators of transformative learning experiences that nurture the values and competencies needed for sustainable living. Grounded in constructivist theory (Piaget, 1970; Vygotsky, 1978; Bruner, 1966), this study emphasizes active, inquiry-based learning as a pathway beyond passive methods

Statement of the problem

However, despite its relevance, Biology education in Nigeria continues to be marked by persistent challenges. Student outcomes, as reflected in internal examinations and external assessments such as the West African Senior School Certificate Examination (WASSCE), reveal patterns of poor performance (WAEC Chief Examiners' Report, 2022). Beyond examination results, many graduates of secondary school still struggle to apply biological knowledge in addressing real-world issues such as waste management, environmental conservation, or even entrepreneurial opportunities in biotechnology-related fields. This disconnect highlights a deeper concern: while students may pass through Biology classrooms, many leave without the innovative mindset required for problem-solving and sustainable living. In this context, AI-enhanced instruction through adaptive learning and simulation platforms offers an opportunity to create such learner-centered environments. However, its effectiveness in enhancing academic performance and fostering a sustainability mindset in Biology classrooms, particularly in comparison to the discussion method, remains underexplored, especially within the Nigerian education system. This gap forms the basis for the present study.

Purpose of the Study

The purpose of this study is to investigate the effects of Artificial Intelligence (AI) on the academic performance and sustainability mindset of senior secondary school students in Biology in Port Harcourt Metropolis, Rivers State. Specifically, the objectives of the study are to:

1. ascertain the difference in academic performance of students in sustainability-related Biology concepts when taught using AI-enhanced instruction and those taught using the discussion method.

2. determine the extent to which teachers utilize AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers state

3. Investigate the challenges teachers encounter in the use of AI-enhanced instructions in teaching Biology in secondary schools in the Port Harcourt metropolis of Rivers state.

Research Questions

The following research questions guided the study:

1. What is the difference in the mean academic performance scores of students in Biology when taught sustainability-related Biology concepts using AI-enhanced instruction and those taught using the discussion method?

2. To what extent do teachers utilize AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers state

3. What are the challenges teachers encounter in the use of AI-enhanced instructions in teaching Biology in secondary schools in the Port Harcourt metropolis of Rivers state

Hypotheses

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

1. There is no significant difference in the mean academic performance scores of students in Biology when taught sustainability-related Biology concepts using AI-enhanced instruction and those taught using the discussion method.

2. There is no significant difference in the mean response of male and female teachers on the extent of utilization of AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers state.

3. There is no significant difference in the mean response of male and female teachers on the challenges that teachers encounter in the use of AI-enhanced instructions in teaching Biology in senior secondary schools in the Port Harcourt metropolis of Rivers State.

Methodology

This study adopted a mixed-method design, combining a descriptive survey with a quasi-experimental approach. The experimental design followed a randomized complete block, pretest, post-test control group format. Two intact classes from four purposively selected public senior secondary schools in Port Harcourt Metropolis (Obio/Akpor and PHALGA LGAs) participated. One group received AI-enhanced instruction using AI simulations and adaptive learning platforms (experimental group), while the other was taught using the conventional discussion method (control group). A total of 240 SS2 Biology students (120 per group) and 60 Biology teachers (34 female, 26 male) were sampled through purposive and stratified random sampling. The survey component captured teachers' perspectives on AI in Biology instruction using a structured instrument: The Questionnaire on Sustainable Mindset in Biology (QSMB). This 3-section, 4-point Likert-scale tool gathered demographic data and teacher responses on AI use. For students, the Biology Performance Test (BPT), a 20-item multiple-choice test aligned with NECO standards, was used as both a pre-test and a post-test on topics like pollution, food security, and conservation of natural resources. Instrument validity was ensured through expert review, while reliability was established using the test-retest method, yielding a coefficient of 0.80 via Pearson's r. (PPMC)

Administration of Instrument

Copies of the questionnaire were administered directly to teachers by the researcher; of the 60 distributed, 55 were successfully retrieved. For the student groups, a pre-test was first administered to both the control and experimental groups. The treatment phase then followed over a four-week instructional period, with the control group taught the selected topics on Ecological Management (Pollution, food security, and Conservation of Natural Resources) using the discussion method, while the experimental group received AI-enhanced instruction through adaptive learning platforms and interactive simulations. For example, instead of only listening to a teacher's explanation, students engaged with computer applications that adjusted questions and content to their individual pace and level of understanding. In the Biology lesson on pollution, the AI platform presented a virtual pollution simulation where students in the experimental class observed how waste disposal affects water and air quality and tested strategies for reducing pollutants. In food

security, adaptive modules provided case-based tasks where students explored sustainable farming practices, with the AI adjusting content to their level of understanding. For conservation of natural resources, interactive simulations enabled students to model the impact of deforestation or overfishing, encouraging them to evaluate sustainable alternatives. These tools provided real-time feedback, ensuring personalized pacing and deeper engagement. Meanwhile, the control group received the same lessons through the traditional discussion method, where the teacher explained concepts, asked questions, and guided group discussions. At the end of the four-week treatment sessions, a post-test was administered to both groups to measure changes in academic performance. Finally, the pre-test and post-test scores were collated and analyzed by the researcher. Research questions were answered using mean and standard deviation, while the hypotheses were tested using the Z-test (two-sample for means) and F-test (two-sample for variances) at the 0.05 level of significance.

Presentation of Results

The retrieved data were analyzed and presented according to the order in which the research questions and hypotheses were stated.

Research Question 1: What is the mean score difference in the academic performance of students in Biology taught sustainability-related Biology concepts using AI-enhanced instruction and those taught using the discussion method?

Table 1.1 Mean and Standard deviation scores of students taught food security, pollution, and conservation of natural resources using AI-enhanced instruction and those taught using the discussion method.

Methods	n	Pre-test		Post-test		Mean gain score	Mean gain diff.
		Mean	SD	Mean	SD		
AI-enhanced instruction	120	3.03	1.44	11.5	2.38	8.54	
							3.62
Discussion	**120**	**2.00**	**1.43**	**6.92.**	**1.42**	**4.92**	

As shown in table 1.1 above, the mean score of students taught food security, pollution and conservation of natural resources using AI-enhanced instruction in the pretest and post-test were 3.03 and 11.57 respectively with a standard deviation of 1.44 and 2.38 while those taught food security, pollution and conservation of natural resources using discussion method had mean scores of 2.00 and 6.92 and a standard deviation of 1.43 and 1.42 in pretest and post-test. This table also revealed that those taught using AI-enhanced instruction got a mean gain score of 8.54, while those taught using the discussion method had a mean gain score of 4.92. The AI-enhanced instruction differed from the discussion method group in the mean performance gain difference score by 3.62. This shows that Students taught food security, pollution, and conservation of natural resources using an AI-enhanced instruction method performed better than their counterparts taught using a discussion method. However, the small difference in values of standard deviations obtained in the

Biology Performance Test indicates clearly that the responses of students to the questions were homogeneous.

Research Question 2: To what extent do teachers utilize AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers State?

Table 1.2: Mean and Standard Deviation of Biology Teachers' Responses on Utilization of AI-enhanced Instruction in Promoting Sustainability Mindset in Port Harcourt Metropolis of Rivers State.

	Biology Teachers' Response							
Utilization of AI-enhanced Instruction in Promoting Sustainability Mindset	**VHE 4**	**HE 3**	**LE 2**	**VLE 1**	**Mean**	**Std. Dev.**	**n**	**Decision**
Teachers create awareness of ecosystem balance through AI-enhanced lessons.	0	3	19	33	1.47	0.61	55	Disagree
Teachers integrate resource conservation concepts into Biology teaching.	0	2	17	36	1.38	0.56	55	Disagree
Teachers adapt AI tools to address pollution control in the environment.	0	1	15	39	1.29	0.50	55	Disagree
Teachers encourage collaboration for biodiversity protection using AI activities.	0	1	13	41	1.24	0.45	55	Disagree
Teachers evaluate students' understanding of climate change with AI resources.	0	0	10	45	1.18	0.39	55	Disagree
Grand Total					**1.31**		**55**	**Disagree**

Standard reference mean = 2.50

Table 2.1 reveals that the mean values 1.47, 1.38, 1.29, 1.24, and 1.18, which correspond to the **indicators** of Ecosystem Balance, Resource Conservation, Pollution Control, Biodiversity Protection, and Climate Change, are all below the reference mean of 2.50. This indicates that Biology teachers in Port Harcourt metropolis utilize AI-enhanced instruction only to a very low extent in promoting sustainability mindset. Furthermore, the relatively small standard deviation values (0.61, 0.56, 0.50, 0.45, and 0.39) indicate that teachers' responses were fairly homogeneous, showing that most teachers shared similar views.

Research Question 3: What are the challenges teachers encounter in the use of AI-enhanced instruction in the teaching of pollution, food security, and conservation of natural resources in the Port Harcourt metropolis of Rivers State?

Table 3.1: Biology Teachers' Response to the Utilization of AI-enhanced instruction in teaching Biology in Port Harcourt metropolis of Rivers State.

Challenges of Teaching Biology	Biology: Teachers' Response SA	A	D	SD	Mean	Std.dev.	n	Decision
Inadequate tech. Infrastructure	28	15	12	0	3.29	0.81	55	Agree
Lack of Technical Skills	10	20	15	10	2.55	1.00	55	Agree
Limited Training Opportunities	15	15	10	15	2.55	1.17	55	Agree
High Cost of AI Tools and Resources	15	20	10	10	2.73	1.06	55	Agree
Assessment challenge	0	30	15	10	2.36	0.78	55	Disagree
Grand Total					**2.70**			

Standard reference means 2.50

Table 3.1 shows that the mean values 3.29, 2.55, 2.55, and 2.73, respectively, which are greater than the standard reference mean of 2.50, indicate that the Biology teachers believed that the following challenges: Inadequate tech. Infrastructure, lack of technical skills, limited training, as well as high cost of digital tools were the challenges that confronts teachers in the utilization of AI simulation and adaptive learning platform in teaching Biology in Port Harcourt metropolis while the mean scores 2.36 which is less than the standard reference mean 2.50 indicates that the Biology teachers thought that assessment challenges were not seen as challenges that confronts teachers in the use of AI adaptive learning platform in teaching waste management, food/nutrition, and conservation in the metropolis. Small differences in the values of standard deviations obtained, which include 0.81, 1.00, 1.17, 1.06, and 0.78, respectively, indicate that the Biology teachers were homogeneous in their responses.

Hypothesis 1: There is no significant difference in the academic performance of students in Biology when taught pollution-waste management, food/nutrition, and conservation using an AI adaptive learning platform and when taught the same concept using a discussion teaching method.

Table 4.1: F-Test Two-Sample for Variance of the performance of Biology students taught pollution-waste management, food/nutrition, and conservation using an AI adaptive learning platform, and those taught with the discussion method

Sources of Variation	DF	n	Mean AI adaptive learning platform	Discussion	F-Cal	F-Cri	Decision
Treatment	119	120	7.3	4.46	2.10	1.35	Rejected

Table 4.1 shows that the calculated f-value for the effect of the AI adaptive learning platform and discussion method on the students' performance in the Biology Performance Test (BPT) is 2.10,

while the f-critical value is 1.35. The calculated f-value is greater than the critical f-value; therefore, the null hypothesis, which stated that there is no significant difference in the academic performance of students in Biology when taught pollution-waste management, food/nutrition, and conservation using an AI adaptive learning platform, and when taught the same concept using the discussion method, is rejected. This implies that a significant difference exists between the two teaching methods (AI adaptive learning platform and discussion method) in the students' performance scores.

Hypotheses 2: There is no significant difference in the mean response of male and female teachers on the extent of utilization of AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers state.

Table 4.2**: z-Test Two Sample for Mean Responses of male and female teachers on the extent of utilization of AI-enhanced instruction in Biology to promote a sustainability mindset in the Port Harcourt metropolis of Rivers state.**

Group	Mean	Std. Dev.	n	DF	Z-Cal	Z-Cri	Decision
Male Students	1.34	0.5	23	53	0.42	1.96	Ho accepted
Female Students	1.28	0.48	32				

Table 4.2 shows the null hypothesis on the z-test of difference in the mean responses of male and female teachers on the extent of utilization of- AI-adaptive learning platform in teaching Biology was accepted at the 5% level of significance. With degrees of freedom df = 53 and a critical value of Z = 1.96, the calculated value Z = 0.42 and is smaller than the critical value. Therefore, the null hypothesis is accepted: there is no significant difference between the mean responses of male (M = 1.34, SD = 0.52, n = 23) and female students (M = 1.28, SD = 0.48, n = 32). This indicates both groups agreed that the sustainability-related Biology concepts were not adequately covered with the use of AI-adaptive learning platform. This hinders the effective promotion of a sustainability mindset among students. This suggests that the limited utilization of AI-enhanced instruction in Biology may negatively impact students' development of a sustainability mindset, highlighting the need for more effective integration of AI in teaching sustainability concepts.

Hypothesis 3: There is no significant difference in the mean responses of male and female teachers on the challenges that teachers encounter in the use of- AI-adaptive learning platform in teaching in senior secondary schools in Port Harcourt metropolis of Rivers State.

Table 4.3: z-Test Two Sample for Mean Responses of male and female Teachers on the confrontation of teachers in the use of AI-adaptive learning platform in teaching Biology in Senior Secondary Schools in Port Harcourt metropolis of Rivers State.

Group	Mean	Std.Dev.	n	DF	Z-Cal	Z-Cri	Decision
Male Teachers	3.11	0.81	23	53	0.51	1.97	Ho Accepted

Female Teachers	2.11	0.94	32

Table 4.3 shows that the null hypothesis on z-test on difference in the mean responses of male female teachers on the challenges that confronts teachers in the utilization of AI- adaptive learning platform in teaching pollution-waste management, food/nutrition, and conservation in senior secondary schools in Port Harcourt metropolis of Rivers State, was accepted at 5% level of significance, where the degree of freedom (53) is not at infinity (∞), because the critical value of z (1.96) is greater than the calculated value of z (0.51). This shows that male and female teachers agreed that Biology teachers were of the view that the following challenges: Inadequate tech. Infrastructure, lack of technical skills, limited training, as well as high cost of digital tools were the challenges that confront teachers in the utilization of AI simulation and adaptive learning platform in teaching Biology in the Port Harcourt metropolis of Rivers State.

Summary of findings shows that: There is a significant difference between the teaching methods, AI-enhanced instruction (simulation and adaptive learning platform) and the discussion teaching method, in the students' mean performance score. Topics such as photosynthesis, waste management, food/nutrition, microorganisms, and conservation were not adequately covered with the use of an AI-enhanced teaching method, which hinders the effective promotion of a sustainability mindset among students. Inadequate tech. Infrastructure, lack of technical skills, limited training, as well as high cost of digital tools were seen as the challenges that confront teachers in the use of AI simulation and adaptive learning platform in teaching Biology in the Port Harcourt metropolis of Rivers State.

Discussion of findings

In research question one and null hypothesis one, findings show that students taught photosynthesis, waste management, food/nutrition, microorganisms, and conservation using an AI-enhanced instruction method performed better than their counterparts taught using the discussion method. The study showed that a significant difference exists between the experimental group (AI-enhanced instruction) and the control group (Discussion method). The researcher associates the relative superiority of the AI-enhanced instruction method over the discussion method of teaching to the fact that the AI-enhanced instruction method engages the learners' sense of sight, feeling, as well as fosters psychomotor skills, whereas the Discussion method fosters verbal description of concepts. This study agrees with the study of Holmes et al. (2022) and Chen et al. (2021), who affirm that AI-driven instruction, through adaptive platforms and interactive simulations, significantly enhances science learning by personalizing content, deepening engagement, and enabling real-world application far beyond Discussion methods.

In research question two and null hypotheses two, the study found that sustainability-related Biology concepts were not adequately covered with the use of an AI-enhanced teaching method, which hinders the effective promotion of a sustainability mindset among students. This finding does not support that of Adeyemo et al. (2023 who emphasized that learning experience associated with AI-enhanced instruction not only promotes problem-solving, creativity, and ecological

responsibility, but also plays a vital role in shaping a sustainability mindset among secondary school Biology students.

In research question three and null hypotheses three, the study found that Infrastructure, lack of technical skills, limited training, as well as the high cost of digital tools, were seen as the challenges that confront teachers in the use of AI simulation and adaptive learning platforms in teaching Biology in the Port Harcourt metropolis of Rivers State. This finding agrees with the stance of Okonkwo and Nwankwo (2021), who highlighted that insufficient infrastructure, lack of technical expertise, and inadequate teacher training were the most outstanding problems mitigating the effective incorporation of AI-enhanced instruction in teaching Biology in senior secondary schools in the metropolis.

Conclusion

This study has demonstrated that AI-enhanced instruction, particularly through simulations and adaptive learning platforms, significantly outperforms conventional discussion methods in teaching sustainability-related Biology concepts at the senior secondary school level. The interactive, personalized, and visual nature of AI tools has proven effective in enhancing student engagement and academic performance, affirming their pedagogical value in modern science education.

However, the study also revealed a critical gap in the ability of AI-enhanced instruction to fully promote a sustainability mindset among students. While the potential of AI to support ecological literacy is well-documented, its effectiveness in this study was limited, particularly in delivering sustainability-related Biology concepts. This shortfall is not inherent to the AI tools themselves but is rooted in broader systemic challenges. Inadequate infrastructures, such as inconsistent power supply, limited access to digital devices, and poor internet connectivity, constrains the effective use of AI in many Nigerian schools. Furthermore, the undertraining of teachers in the integration of AI tools weakens the instructional quality and limits the depth of coverage required to instill sustainability-oriented thinking.

Therefore, while AI-enhanced instruction shows clear promise for improving Biology education, its transformative potential, especially in nurturing students' sustainability consciousness, remains largely untapped. For AI to contribute meaningfully to both academic achievement and the cultivation of ecological responsibility, deliberate efforts must be made to strengthen digital infrastructure, expand access to technological resources, and equip teachers with the necessary skills for effective implementation. Only then can AI fulfill its role not just as a tool for instruction, but as a catalyst for shaping environmentally responsible and future-ready learners.

Recommendations

Based on the findings of this study and their implications for Biology education in the 21st century, the following recommendations are proposed to enhance the integration and effectiveness of AI-enhanced instruction; specifically, AI simulations and adaptive learning platforms; in teaching sustainability-focused Biology topics such as photosynthesis, waste management, food and nutrition, microorganisms, and conservation: First, investment in educational technology must be prioritized to provide schools with reliable digital infrastructure, including internet access, devices, and stable power supply, enabling consistent use of AI tools. Second, ongoing teacher capacity

building is essential. Regular, targeted training programs should equip Biology teachers with the skills needed to effectively implement AI-enhanced methods and maximize their educational benefits. Third, curriculum reform and policy support are needed to embed AI-based teaching strategies into national Biology syllabi, ensuring alignment with contemporary educational goals and sustainability priorities. Fourth, recognition and incentives for teachers innovating with AI can motivate greater adoption and commitment, while timetable adjustments should allow adequate classroom time for AI-driven activities. Finally, fostering global collaboration and research will help refine AI applications for local contexts and provide evidence of their long-term impact on student learning and sustainability mindset development.

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