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ORIGINAL

Integrating Generative AI into Bioenergetics Modules: A PAIRR-Based Approach for Senior High School Biology

Integración de la Inteligencia Artificial Generativa en los Módulos de Bioenergética: Un Enfoque Basado en el Modelo PAIRR para la Enseñanza de la Biología en la Educación Media Superior

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ABSTRACT

Introduction: artificial intelligence (AI) offered transformative potential for enhancing learning and academic support, but its systematic integration into science-specific modules aligned with DepEd guidelines had not been fully explored. Bioenergetics, a complex topic in senior high school biology, remained a persistent challenge for learners.
Method: the study developed a Generative AI-integrated bioenergetics module using the Peer and AI Review + Reflection (PAIRR) approach. A mixed-method design combined quantitative analysis with qualitative support. Module validation assessed Student Involvement Index, feedback-based readability, and Communication Index. A limited trial was conducted with 64 11th grade learners. Achievement scores before and after module use were analyzed using the Wilcoxon Signed Rank test, and post-implementation interviews captured learner perceptions.
Results: the module achieved acceptable validation scores for Student Involvement Index (1,08), feedback-based readability, and Communication Index (0,003). Learners' achievement scores improved significantly after using the module ($p < 0,05$). Students reported that AI provided personalized support, clarified complex bioenergetics concepts, and enhanced engagement. Challenges included intermittent internet connectivity, uneven group participation, time constraints, and initial difficulty using ChatGPT.
Conclusions: the Generative AI-integrated module effectively enhanced learners' understanding of bioenergetics, demonstrating AI's potential as a collaborative peer in science education. Further research should evaluate scalability, long-term impact, and adaptability across other science topics.

Keywords: AI Integration in Education; AI Feedback; Bioenergetics; Science Education; Module Learning.

RESUMEN

Introducción: la inteligencia artificial (IA) ofreció un potencial transformador para mejorar el aprendizaje y el apoyo académico, pero su integración sistemática en módulos específicos de ciencias, alineados con las directrices del Departamento de Educación, no se había explorado a fondo. La bioenergética, un tema complejo en la biología de secundaria, seguía siendo un desafío persistente para los estudiantes.
Método: el estudio desarrolló un módulo de bioenergética integrado con IA generativa utilizando el enfoque de Revisión y Reflexión por Pares e IA (PAIRR). Un diseño de método mixto combinó análisis cuantitativo

con apoyo cualitativo. La validación del módulo evaluó el Índice de Participación Estudiantil, la legibilidad basada en la retroalimentación y el Índice de Comunicación. Se realizó un ensayo limitado con 64 estudiantes de 11.º grado. Se analizaron las puntuaciones de rendimiento antes y después del uso del módulo mediante la prueba de rangos con signos de Wilcoxon, y las entrevistas posteriores a la implementación recogieron las percepciones de los estudiantes.
Resultados: el módulo obtuvo puntuaciones de validación aceptables en el Índice de Participación Estudiantil (1,08), la legibilidad basada en la retroalimentación y el Índice de Comunicación (0,003). Los resultados de los estudiantes mejoraron significativamente tras el uso del módulo ($p < 0,05$). Los estudiantes informaron que la IA les brindó apoyo personalizado, les aclaró conceptos complejos de bioenergética y mejoró su participación. Las dificultades incluyeron la conectividad a internet intermitente, la participación desigual del grupo, las limitaciones de tiempo y la dificultad inicial con ChatGPT.
Conclusiones: el módulo integrado con IA Generativa mejoró eficazmente la comprensión de los estudiantes sobre la bioenergética, demostrando el potencial de la IA como herramienta colaborativa en la educación científica. Se recomienda que futuras investigaciones evalúen la escalabilidad, el impacto a largo plazo y la adaptabilidad a otros temas científicos.

Palabras clave: Integración de la IA en la Educación; Retroalimentación de IA; Bioenergética; Educación Científica; Aprendizaje por Módulos.

INTRODUCTION

Bioenergetics was a fundamental topic in biology that examined the energy transformations within living organisms. For senior high school learners, understanding processes such as photosynthesis and cellular respiration was essential for comprehending the mechanisms sustaining life. However, these concepts were challenging to teach, as students often struggled with the abstract nature of energy conversion and the complex relationships among metabolic pathways.[1,2] Traditional instructional methods had shown limited success in addressing these difficulties, highlighting the need for innovative approaches. Recent studies emphasized the value of modules and intervention materials for improving conceptual understanding and motivation in science learning.[3,4]

Globally, artificial intelligence (AI) had transformed education by fostering personalized learning, streamlining administrative tasks, and introducing innovative teaching strategies—trends accelerated by the COVID-19 pandemic and the adoption of extended reality tools.[5] The Peer and AI Review + Reflection (PAIRR) approach[6] aligned with pedagogical frameworks that treated AI as a collaborative learning partner and leveraged peer review for metacognitive development and rhetorical reasoning.[7] It further reflected teacher-led, ecological models emphasizing instructor agency, structured peer evaluation, and scaffolding for student interactions with AI outputs.[8] By combining peer feedback, AI-generated review, and structured reflection, PAIRR supported formative assessment and encouraged student independence while positioning AI as a partner rather than a replacement for human judgment.

In the Philippine context, AI tools such as ChatGPT had been explored for language learning[9] and academic support.[10] However, challenges persisted, including inadequate technological infrastructure, ethical concerns, and inequitable access to AI resources.[11] While AI demonstrated transformative potential, its successful integration required careful attention to local contexts and sustained collaboration among educators, policymakers, and technology developers. Despite these developments, systematic integration of AI into science-specific modules—especially for complex topics like bioenergetics—remained underexamined. Furthermore, limited research addressed embedding generative AI into structured learning materials aligned with DepEd guidelines.[12]

Anchored on these gaps, this study aimed to develop a Generative AI-integrated module on bioenergetics. Specifically, it sought to (1) analyze the needs of teachers and students in science education, (2) design the Generative AI module on bioenergetics, and (3) develop the module to enhance students' understanding of bioenergetics concepts.

METHOD

This study employed a quantitative design supported by qualitative data to comprehensively evaluate the effectiveness of a Generative AI-integrated module in enhancing students' understanding of bioenergetics. The investigation was done in the Division of Malaybalay during the 2nd grading period of S.Y. 2025-2026.

Participants and Sampling

The needs assessment employed purposive sampling to ensure that participants possessed relevant experience

in teaching and learning biology. One (1) school head and four (4) biology teachers from the selected senior high school were included based on the following inclusion criteria: currently employed at the institution, directly involved in the 11th grade science curriculum, and willing to provide insights on the integration of project-based learning and AI tools. Six (6) 11th grade students were likewise purposively invited to represent varying levels of academic performance in biology (high, average, and low) to obtain diverse perspectives on learning needs. Only those who submitted signed assent and parental consent forms were included; students who declined or failed to complete consent requirements were excluded.

For the implementation phase, intact class sampling was used to maintain natural classroom settings and avoid disruption. Two 11th grade General Academic Strand (GAS) sections were selected based on their availability during the second grading period of School Year 2025–2026, totaling 64 bona fide students (28 males and 36 females). Inclusion criteria required that participants be officially enrolled in the school and have completed the first grading period in the same strand. Students who were absent during pretest or posttest administration or withdrew mid-semester were excluded from data analysis. Participation was voluntary, and informed consent and assent were obtained in compliance with institutional ethical protocols.

Ethical Consideration

The research related to human use has been complied with all the relevant national regulations and institutional policies. All participants were informed of the study's purpose, procedures, and their rights, including voluntary participation and confidentiality. Informed consent was obtained before data collection. There were no conflicts of interest, and participant data was handled with strict confidentiality and anonymity.

Instructional Design Framework: ADDIE Model

The module was developed following the ADDIE model—Analysis, Design, Development, Implementation, and Evaluation—to ensure systematic instructional design.

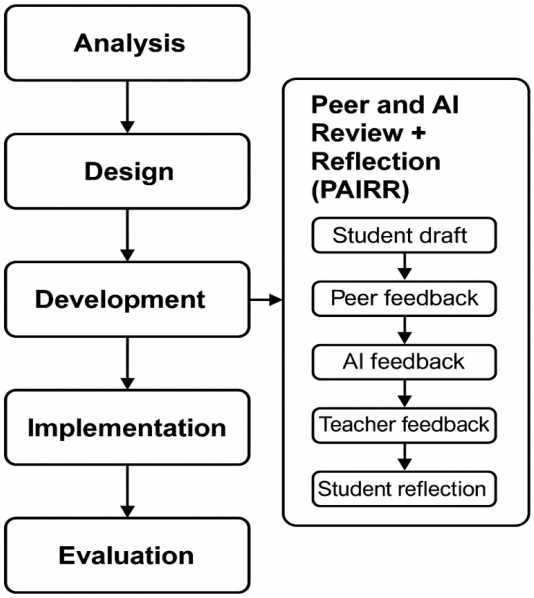

Figure 1. Workflow diagram illustrating the integration of the ADDIE instructional design model with the Peer and AI Review + Reflection (PAIRR) feedback process for module development and evaluation

Analysis Phase

A needs analysis was conducted using semi-structured interviews guided by a researcher-developed protocol. Seven open-ended questions probed participants' experiences with project-based science, existing instructional materials, and perspectives on AI integration. Each interview lasted 30–40 minutes. To minimize bias, two independent reviewers coded the transcripts, and disagreements were resolved through discussion with a third reviewer.

Design Phase

Insights from the analysis informed the module's structure, learning objectives, and pedagogy. Objectives were aligned with the Department of Education K–12 science curriculum. The module comprised three lessons—A Look into Bioenergetics, A Synthesis on Photosynthesis, and Cellular Respiration—organized into elicitation of prior knowledge, explanation, assessment, elaboration, evaluation, and extension activities. Generative AI

(ChatGPT) was embedded as a peer collaborator and feedback provider following the Peer and AI Review + Reflection (PAIRR) approach (Sperber et al., 2024). The PAIRR flow—student draft → peer feedback → AI feedback → teacher feedback → student reflection → final answer—was used to encourage deeper cognitive engagement rather than passive AI use.

Development Phase

The draft module underwent content validation by a panel of experts against five parameters: (1) congruence of curriculum material with objectives, (2) student involvement, (3) cognitive demand, (4) readability, and (5) appropriateness of ChatGPT integration. Validators reviewed all lesson components (*Elicit*, *Explore*, *Elaborate*, *Evaluate*, *Extend*). Validation scores were highly acceptable across parameters.

Implementation Phase

A three-week limited trial was conducted with the two intact 11th grade classes. Lessons were facilitated by the researchers, who ensured standardized delivery.

Evaluation Phase

A researcher-made achievement test was administered to the students before and after the limited trial. This questionnaire consisted of 40 multiple-choice items covering the following competencies: (1) trace the energy flow from the environment to the cells – S11/12LT-IIbd-6, (2) describe how organisms obtain and utilize energy – S11/12LT-IIbd-7, and (3) recognize that organisms require energy to carry out functions necessary for life – S11/12LT-IIbd-8. The questionnaire was pilot tested to 183 Grade 12 students. The internal consistency reliability measures of the achievement test are shown in table 1 below.

Table 1. Internal consistency reliability of biology test

SN	Indicator	Value
1	Number of Item	40
2	Kuder Richardson (KR-20)	0,8166
3	Kuder Richardson (KR-21)	0,7892
3	Cronbach's Alpha Based on Standardized Items	0,8155
4	Mean Difficulty Index	0,6509
5	Mean Discrimination Index	0,3564

In addition to the quantitative measures, qualitative data were gathered to enrich the findings and provide deeper insights into the students' and teachers' experiences with the module. Semi-structured interviews were conducted with both students and teachers after the limited trial of the module.

Data Analysis

Pre- and post-test scores were analyzed using descriptive statistics and the Wilcoxon Signed Rank test, referencing Department of Education Order No. 8, Series of 2015, for grading scale interpretation (table 2). Qualitative data from post-implementation interviews with students and teachers were analyzed thematically using in-vivo coding. To enhance credibility and minimize bias, two independent coders reviewed transcripts, and a third expert adjudicated discrepancy. Triangulation between quantitative and qualitative findings ensured a comprehensive interpretation of results.

Table 2. Scoring procedure tailored from D.O no. 8, series of 2015

Achievement Level	Grading Scale
Outstanding	34-40
Very Satisfactory	31-33
Satisfactory	27-30
Fairly Satisfactory	24-26
Did not meet expectations	Below 24

The collected qualitative data were analysed thematically using in-vivo coding and triangulated with two (2) other experts to validate the results, allowing for the identification of common themes and patterns in the participants' responses.

RESULTS

Needs Analysis

The following sections present findings on the one-on-one interview done. This is divided into two (2) themes; Learning difficulties and the use of ChatGPT in the classroom. To start with, the science teachers were asked about the topics in biology that their students find difficult, based on their assessments and evaluation. The topic on Bioenergetics emerged as a common theme to their answers, as shown in table 3.

Table 3. Learning difficulties of students and teachers in science

Emergent themes	Codes	Illustrative Excerpts
Learning difficulties	Bioenergetics as a subject	"In my teaching career, especially during the second grading period, students really struggle with the concept of photosynthesis because we are dealing with a more complex and deeper understanding of it. This is further compounded by the fact that we cannot see it." (T1) "Also, things like photosynthesis and respiration can be tricky because they have so many steps. They are complex and difficult to memorize." (L2)
	Lack of materials	"I also believe that there are limitations such as the availability of resources in the rural areas. There were the lack of books, activity sheets, and modules" (T4). "Some materials, like books, are lacking, so we just have to share with each other." (L3)
	Difficulty of existing materials	"The modules we use have a lot of activities, making them difficult to keep up with." (L4) "Some parts of the books and modules are very difficult to understand, especially when there are terms we don't know." (S5)

Bioenergetics is the main component of the general biology curriculum for the 2nd grading. These are divided into topics like, photosynthesis, respiration, ATP-ADP cycle. These could have been the answers of 2 of our teachers and 3 of our students as these are the current topics being discussed. Students commonly describe bioenergetics as "complex" and hard to understand. High school students, both internationally and in the Philippines, often find bioenergetics challenging due to several interrelated factors.

Teaching strategies go hand-in-hand with the learning resources available. The interview showed the different challenges to the learning resources available to the science teachers and students. The lack of materials and the difficulty in using the existing materials were the common sentiments regarding the school learning materials. The modules and books were available but the students find them bombarded with activities and some are not suited to their level.

The integration of ChatGPT in educational settings has garnered significant attention from both students and teachers, highlighting its potential to enhance learning experiences. Table 4 sheds light on the teacher and student's use of ChatGPT, and their perceived benefits and challenges.

Table 4. Challenges and Benefits of ChatGPT in Education

Emergent themes	Codes	Illustrative Excerpts
Challenges in using ChatGPT	Over-reliance	"The challenge would be that students would halt their creative thinking if they rely too much in AI." (T2) "Over reliance on the tool that further makes them lazy to think and show their creativity". (T3)
	Learning negligence	"They just rely on others, and we know that sometimes ChatGPT's answers are wrong, but we still use them because we're in a hurry." (L3) "Even if you're not really knowledgeable about the topic, your answers still look good—even if you don't truly understand them." (L6)
Benefits of using ChatGPT	Critiquing and Feedbacking, Collaboration,	"It can make the process of brainstorming and research faster. It could also offer critics and feedback for their ideas, allowing them to improve more on what they currently have." (T1) "We can think more easily because we can quickly ask ChatGPT." (L3)
	Learning assistance	"It gives us ideas and suggestions, especially when we're struggling to start our assignments or projects." (L2) "It really helps us, ma'am, especially in summarizing long and difficult topics" (L4)

The integration of ChatGPT in educational settings has garnered significant attention from both students and teachers, highlighting its potential to enhance learning experiences. Teachers have noted its utility in creating instructional materials and assisting with writing tasks, thereby streamlining educational processes. However, concerns regarding academic integrity, technological dependence, and the need for pedagogical support have been raised, emphasizing the importance of structured integration into curricula.

Development of the module

Initial expert feedback gave low scores to the Elicit part, particularly regarding the student involvement in the module. Readability of the module also received a score of 3. Based on the comments of the evaluators, the identified section was improved through adding checkpoint questions and highlighting important words. Final evaluation scores are shown in table 5, below.

Table 5. Results of the evaluation ratings

Lesson and lesson components	Congruence of curriculum material with its objectives	Student involvement in the module	Cognitive demand of the module	Readability of the module	Appropriateness of ChatGPT use
Lesson 1: A Look into Bioenergetics					
Elicit	4	3,33	4	4	4
Explore	4	3	4	3	4
Elaborate	4	4	4	4	4
Evaluate	4	4	4	4	4
Extend	4	4	4	4	4
Lesson 2: A Synthesis on Photosynthesis					
Elicit	4	3,33	4	4	4
Explore	4	3	4	3	4
Elaborate	4	4	4	3	4
Evaluate	4	4	4	4	4
Extend					
Lesson 3: Cellular Respiration					
Elicit	4	3,33	4	4	4
Explore	4	3	4	3	4
Elaborate	4	4	4	4	4
Evaluate	4	4	4	4	4
Extend	4	4	4	4	4

Note: 1 = Not Acceptable. Major Modification Needed, 2 = Below Expectations. Some Modification Needed, 3 = Expectation Meet. No Modification is needed but it can be Improved with minor changes, 4 = Exceed Expectation. No Modification Needed

Evaluation of the module

Table 6. Profile of Pre-test and Post-test scores in Bioenergetics

Achievement level	Frequency	
	Pretest	Post-test
Outstanding	0	6
Very satisfactory	4	15
Satisfactory	14	27
Fairly satisfactory	15	10
Did not meet expectations	31	6
Mean score	16,429	25,952
s.d.	4,054	5,367
Achievement level	Did not meet expectations	Fairly Satisfactory
Z	-4,018	
Wilcoxon asymptotic significance	0,001	

In table 6, it is evident that there was a notable increase in the learners' achievement level. The Wilcoxon Signed Rank test showed a p-value of 0,01 which is less than α=0,05. This means that there is enough statistical evidence to accept the alternative hypothesis which further implies that the material is effective in increasing the achievement scores of the 11th grade learners in bioenergetics. Despite the overall improvement in student performance, six (6) learners still did not meet expectations, which could be attributed to several factors.

From the thematic analysis of the interview after the implementation, it is evident that learners had a largely positive experience with the Generative AI-integrated modules. The interactive nature of the lessons and the use of ChatGPT were major positives, as they helped learners actively engage with the material, clarified concepts, and provided immediate feedback. These insights are evident in the emergent theme 1 in table 7, below.

Table 7. Emergent themes based on learners' insights into their experience with the Generative AI-integrated modules

Emergent themes	Codes	Selected Responses
Positive experiences in the use of the modules	Interactive learning experiences, Student engagement Student Interest	"The activities helped me learn because I was not just reading, I was also doing tasks like making a project about bioenergetics." (L15). "It made the lessons more interesting because I was doing real tasks, not just reading or answering tests." (L1)
	Learning assistant	"ChatGPT explained things in simple ways when I did not understand, which helped me learn." (L10). "ChatGPT made it easier to understand hard topics because it explained them step by step." (L21)
	Immediate feedback	"It was like having a teacher I could ask anytime. It saved time because I did not have to wait for someone to explain." (L1) "It helped me check if I understood the lessons correctly by giving more examples." (L12)

Significant challenges were put into highlight in Theme 2, Challenges in the use of the module as illustrated in table 8. Group dynamics were an issue, with some learners relying too heavily on team leaders, which may suggest a lack of balanced participation. Internet connectivity problems also emerged, which is a common barrier in online learning environments. While the modules showed promise, the feedback suggests that further adjustments—such as extending the learning time, improving group participation, and providing more guidance on using AI tools—could improve the learning experience.

Table 8. Emergent themes based on learners' insights into their experience with the Generative AI-integrated modules

Emergent themes	Codes	Selected Responses
Challenges in the use of the module.	Poor internet connection	"It was hard to use the internet sometimes because it was slow." (L12)
	Group Dynamics	"Some members of the group just rely on the team leaders" (L1)
	Time management	"The activities took a lot of time to finish." (L14)
	Poor skills in using ChatGPT	"At first, I didn't know how to use ChatGPT properly." (L3)
Points to improve	Learning Pace	"Give more time to work on the activities and projects." (L17). "If we had more time to explore and think about our projects, I think the learning experience would be even better." (L19)

The findings of this study demonstrate the potential of integrating AI, specifically ChatGPT, in learning modules to enhance student understanding of Bioenergetics. The modules yielded positive results in terms of student achievement, with a statistically significant improvement observed from pretest to posttest scores. While some learners still require additional support, the overall improvement suggests that the intervention effectively facilitated learning. Furthermore, the positive feedback from learners indicates that the modules were engaging and fostered a deeper understanding of the subject matter.

DISCUSSION

This study addressed persistent learning challenges in Grade 11 bioenergetics by developing and implementing

a Generative AI–integrated module. The results revealed notable improvements in students' conceptual understanding, engagement, and motivation. Qualitative feedback indicated that the integration of ChatGPT enhanced clarity in abstract concepts such as photosynthesis and cellular respiration, promoted self-directed learning, and encouraged collaboration. However, challenges related to time constraints, uneven participation, and limited access to technology remained.

The findings confirmed long-standing observations in both international and Philippine contexts that bioenergetics remains one of the most conceptually difficult areas of biology.[1,2] Similar to these studies, students initially demonstrated misconceptions about energy flow and metabolic processes, underscoring the limitations of traditional, teacher-centered instruction. The improvement observed after implementing the AI-integrated module aligns with reports that AI can scaffold complex learning through real-time feedback and personalized support.[3,5]

The enhanced engagement noted in this study can be attributed to AI's dialogic and interactive nature. Students' opportunities to ask ChatGPT, receive immediate clarification, and test their reasoning likely promoted metacognitive awareness—an effect supported by the cognitive apprenticeship model.[13] Recent research supports this by demonstrating how AI-driven interactive scaffolding supports self-regulated learning behaviors such as goal-setting, self-evaluation, and motivation.[14,15,16] Furthermore, it is argued that generative AI facilitates a shift from passive reception to active exploration, a mechanism that appears to explain the heightened interest and participation observed here.[17,18] Additionally, AI's real-time feedback mechanisms reinforce understanding by allowing learners to quickly recover from errors and adapt their approaches.[19]

However, the effectiveness of the AI-integrated module was influenced by contextual constraints commonly experienced in Philippine public schools, particularly inconsistent internet connectivity, limited device availability, and varying levels of digital literacy among students. These factors moderated the otherwise positive learning gains observed during implementation. Such findings are parallel to claims that emphasized that equitable technological access and structured pedagogical support are essential for successful AI integration.[11,20,21] Similarly, international studies have reported that without adequate infrastructure and teacher facilitation, the potential benefits of AI in education may not be fully realized.[5,18] Therefore, while generative AI proved effective in promoting conceptual scaffolding and engagement, its impact in this study remained contingent upon teacher mediation, institutional readiness, and the availability of reliable technological resources.

The results provide empirical support for integrating generative AI in science education to improve student's understanding of bioenergetics, particularly when embedded within a modular learning structure. For teachers, the findings underscore the need to treat AI not as an independent tutor but as a pedagogical partner that extends classroom interaction. For curriculum developers, this research highlights the importance of designing AI-assisted materials that are developmentally appropriate, culturally contextualized, and aligned with local learning standards. Policymakers should likewise consider the infrastructure and capacity-building demands that accompany AI integration, including teacher digital literacy and equitable access to technology.

Despite promising results, the study had several limitations. First, the sample size was limited to two intact Grade 11 classes from a single school, which restricts generalizability. Second, the short implementation period may not have captured long-term learning retention or the full potential of AI integration. Third, although ChatGPT facilitated real-time feedback, its responses occasionally required teacher verification to ensure scientific accuracy. Finally, technological barriers—such as unstable internet connectivity and limited device availability—may have influenced participation and performance. Future research should involve larger, more diverse samples, longitudinal designs, and controlled comparisons to better evaluate the sustained impact of AI integration in science education.

CONCLUSIONS

The bioenergetics modules integrated artificial intelligence through the Peer and AI Review + Reflection (PAIRR) approach and were validated for content, student involvement, cognitive demand, readability, and appropriate ChatGPT use. Results from the limited trial demonstrated a statistically significant improvement in student achievement, confirming the module's effectiveness in enhancing learners' understanding of bioenergetics. Students valued the interactive activities and immediate feedback provided by ChatGPT, which clarified complex concepts and supported engagement.

However, several challenges were identified, including poor internet connectivity, reliance on team leaders during group tasks, time constraints, and initial difficulties in using ChatGPT. Learners suggested extending activity time and offering clearer guidance on AI use to improve the learning experience.

To maximize the potential of Generative AI–integrated modules, larger-scale trials across diverse schools are recommended to validate their effectiveness and scalability. Strengthening technological infrastructure is essential to address connectivity issues and ensure equitable access to AI resources. Additionally, comprehensive teacher training programs are needed to equip educators with the skills required for effective AI integration. Future research should also explore adapting the Generative AI module to other science topics to evaluate its broader applicability and long-term impact on STEM education.

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CONFLICT OF INTEREST

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