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Development of an Adaptive Biology E-Module Using Generative AI and Personalized Learning to Enhance Self-Directed Learning

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Abstrak- This study aims to develop and evaluate an Adaptive Biology E-Module assisted by Visual Generative AI with a Personalized Learning Path to enhance students' self-directed learning. The study employed a Research and Development (R&D) approach using the ADDIE model, consisting of analysis, design, development, implementation, and evaluation stages. The research was conducted with Grade X students at SMAN 6 Tanjungpinang, Indonesia. Data were collected through needs-analysis questionnaires, teacher interviews, diagnostic assessments, expert validation sheets, practicality questionnaires, self-directed learning scales, and pretest–posttest assessments. The developed e-module integrates diagnostic assessment, adaptive learning content, AI-generated biological visualizations, interactive activities, formative assessment, feedback, and personalized learning pathways based on students' initial competence and learning progress. The projected results indicate an increase in the overall self-directed learning score from 65.3 before implementation to 91.0 after implementation, with improvements across learning awareness, learning strategies, learning activities, self-evaluation, and learning responsibility. These findings suggest that integrating adaptive learning mechanisms, scientifically validated Visual Generative AI, and Personalized Learning Paths has the potential to provide more individualized and meaningful Biology learning experiences. The study contributes a technology-enhanced instructional framework for promoting students' autonomy and self-directed learning in Biology education

Keywords: *adaptive biology e-module; visual generative AI; personalized learning path; self-directed learning; biology education*

1 Introduction

The rapid transformation of digital education has shifted the role of learning resources from static repositories of information toward interactive environments capable of supporting students' active engagement, autonomy, and individual learning needs. This transformation is particularly relevant to biology education because many biological processes involve complex structures, microscopic mechanisms, and dynamic interactions that are difficult to understand solely through textual explanations. Digital learning environments can provide students with multiple representations and opportunities to explore scientific concepts beyond conventional classroom instruction. Tang (2024) emphasized that multimodality and representation are central to science learning and can provide an important foundation for the educational use of generative artificial intelligence (GenAI). Technology-supported learning has also been associated with students' perceptions of greater opportunities for self-directed learning when digital tools are meaningfully integrated into classroom activities (Labonté & Smith, 2022). In the Indonesian context, the development of mobile-based instructional media similarly demonstrates the continuing need for digital learning resources that move students beyond conventional concept delivery toward more active technology-supported learning (Alfirahmani et al., 2025). Therefore, biology learning resources should be designed not merely to digitize textbooks but to facilitate meaningful, interactive, and learner-responsive experiences.

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Electronic modules constitute one promising form of digital learning resource because they can integrate textual explanations, illustrations, multimedia, learning activities, assessment, and feedback within a structured learning environment. However, many existing electronic modules still follow a relatively linear design in which all learners receive the same content, sequence, difficulty level, and learning activities regardless of differences in prior knowledge or learning progress. Such uniformity limits the potential of digital learning to address individual learning needs. Research on adaptive learning systems indicates that effective adaptive environments require systematic consideration of learners, educators, learning content, and the mechanisms through which learning experiences are adjusted (Martin et al., 2024). Gerard et al. (2022) further demonstrated the importance of customizing science curricula to support students in developing self-directed learning processes rather than merely delivering predetermined content. At the local level, interactive module development has also shown increasing attention to integrating instructional approaches and contextual learning resources rather than presenting content as static digital material (Najha et al., 2026). These developments indicate a need to advance electronic modules toward adaptive e-modules capable of modifying learning experiences according to students' competencies and progress.

Adaptive learning becomes particularly powerful when it is combined with a personalized learning path, in which students are not required to progress through identical learning sequences. Instead, diagnostic information can be used to determine the content, learning activities, scaffolding, and level of complexity that are most appropriate for each learner. Recent research provides evidence that GenAI can facilitate this personalization. Jauhiainen and Garagorry Guerra (2024), for example, investigated the dynamic personalization of school learning materials with ChatGPT and demonstrated the feasibility of adjusting learning material according to pupils' knowledge levels. The emergence of GenAI therefore expands the possibility of moving from predetermined personalization toward dynamically generated learning support. Yu and Guo (2023) argue that generative artificial intelligence has significant potential to transform educational practices through personalized content generation, intelligent assistance, and more flexible learning experiences. At the same time, adaptive systems should not be understood only as technological mechanisms; they need pedagogically meaningful designs that respond to students' learning characteristics. This distinction is critical because personalization should enable students to follow learning pathways appropriate to their readiness rather than simply provide more digital content.

A particularly promising application of GenAI in biology education is AI-generated scientific visualization. Biological concepts such as cellular processes, photosynthesis, genetic mechanisms, ecological interactions, and organ systems often require learners to coordinate information across different spatial and representational levels. GenAI can potentially generate contextualized illustrations, diagrams, visual explanations, and other multimodal representations that make abstract scientific phenomena more accessible. Tang (2024) argues that research on GenAI in science education should draw on established knowledge about multimodality and scientific representations because meaning-making in science depends on interactions among linguistic, visual, symbolic, and other representational modes. A systematic review by Ogunleye et al. (2024) similarly indicates that GenAI provides emerging opportunities for content generation and personalized support in teaching and learning, while simultaneously requiring careful pedagogical implementation. In Indonesian digital-learning research, interactive virtual media have also demonstrated that visual and simulated learning experiences can contribute to improved cognitive learning outcomes when integrated with appropriate instructional strategies (Dwi et al., 2026). Consequently, visual Generative AI in an adaptive biology e-module should function as pedagogical scaffolding rather than merely as an aesthetic feature.

Nevertheless, the educational integration of GenAI requires more than generating attractive images or automatically producing instructional content. GenAI-supported resources should direct learners toward meaningful cognitive engagement, provide appropriate scaffolding, and maintain students' responsibility for regulating their own learning. Ng et al. (2024) found that ChatGPT-supported learning can facilitate students' self-regulated learning and science education when the technology is positioned as learning support rather than a substitute for students' thinking processes. Evidence from science education also shows that self-directed learning requires learners to engage in planning, monitoring, information integration, and decision-making, which can become cognitively demanding without appropriate instructional guidance (Uus et al., 2022). Gerard et al. (2022) similarly highlighted the importance of well-designed digital science resources and teacher support for fostering productive self-directed science learning. Therefore, GenAI integration in biology education should be designed to gradually strengthen students' capacity to make learning decisions rather than creating new dependence on automated assistance.

Self-directed learning is especially relevant because digital learning increasingly requires students to take responsibility for setting goals, selecting learning strategies, monitoring progress, and evaluating learning outcomes. Technology alone, however, does not automatically produce learning autonomy. Labonté and Smith (2022) found that students' experiences of self-directed learning are influenced by how technology is incorporated into learning activities, suggesting that digital tools must be accompanied by instructional designs that deliberately encourage autonomy. Uus et al. (2022) further showed that school students can construct scientific knowledge through self-directed activities, although the process requires sufficient cognitive and metacognitive support. Indonesian evidence likewise suggests that technology-supported self-directed learning can contribute to the development of higher-order competencies when learning environments provide students with greater responsibility for their learning processes (Baharuddin et al., 2022). Thus, an adaptive biology e-module should provide structured opportunities for students to identify their learning needs, select appropriate learning pathways, obtain feedback, and independently evaluate their progress.

Recent developments in electronic-module research also demonstrate a growing interest in integrating GenAI into digital instructional materials. A recent needs analysis by Aden et al. (2026) identified substantial demand for electronic modules integrating Generative AI, animated visualization, multimedia, and student-centered learning components. Their findings provide an empirical indication that learners and teachers require digital resources that extend beyond conventional electronic texts toward richer visual and interactive environments. Previous JoSLEPI research has similarly explored Android-based digital instructional media (Alfirahmani et al., 2025), virtual laboratory-supported instruction (Dwi et al., 2026), and interactive module development incorporating instructional strategies (Najha et al., 2026). Collectively, these studies demonstrate continuing innovation in technology-enhanced science learning. However, they also reveal an opportunity to move beyond digital interactivity toward systems that adapt visual representations, learning activities, and learning sequences according to individual student needs.

Despite the rapid expansion of GenAI research, a significant research gap remains at the intersection of adaptive biology e-modules, visual Generative AI, personalized learning paths, and students' self-directed learning. Existing research has examined GenAI-supported science learning, multimodal scientific representation, electronic modules, adaptive learning, and personalized learning, but these components have largely developed as separate research strands. Tang (2024) specifically calls for stronger connections between GenAI and established science-education research on representation and multimodality. Jauhiainen and Garagorry Guerra (2024) demonstrated dynamic personalization using GenAI, yet their work was not specifically designed as an adaptive biology e-module centered on AI-generated scientific visualization. Furthermore, existing research on adaptive learning highlights continuing limitations in stakeholder-informed and pedagogically grounded system development (Martin et al., 2024). This gap suggests that there is a need for a learning environment that does not merely incorporate GenAI as an additional technological feature but systematically connects learner diagnosis, adaptive content, AI-generated visual scaffolding, and individualized progression.

Accordingly, the novelty of the present study lies in the integration of Visual Generative AI and a Personalized Learning Path within an adaptive biology e-module designed specifically to promote students' self-directed learning. The proposed module begins by identifying students' initial learning profiles through diagnostic activities and subsequently directs learners to differentiated pathways based on their level of understanding. Visual GenAI is incorporated to provide contextualized scientific illustrations and visual scaffolding appropriate to the learning content, while adaptive activities, formative assessments, and feedback are used to continuously guide subsequent learning pathways. This design differs from conventional e-modules that provide identical content and sequences to all students and from GenAI applications that function primarily as general-purpose conversational assistants or content generators.

2. Research Methodology

Research Design

This study employed a Research and Development (R&D) approach using the ADDIE framework, comprising five systematic stages: Analysis, Design, Development, Implementation, and Evaluation. The research was conducted at SMAN 6 Tanjungpinang, Tanjungpinang City, Riau Islands Province, Indonesia, an accredited public senior high school located in Senggarang. The participants were Grade X students enrolled in Biology courses. During the field implementation, two comparable classes were involved: an experimental class using the Adaptive Biology E-Module assisted by Visual Generative AI with a Personalized Learning Path and a control class receiving regular learning materials. The final number of participants was determined based on the intact classes available during the study.

The Research Process

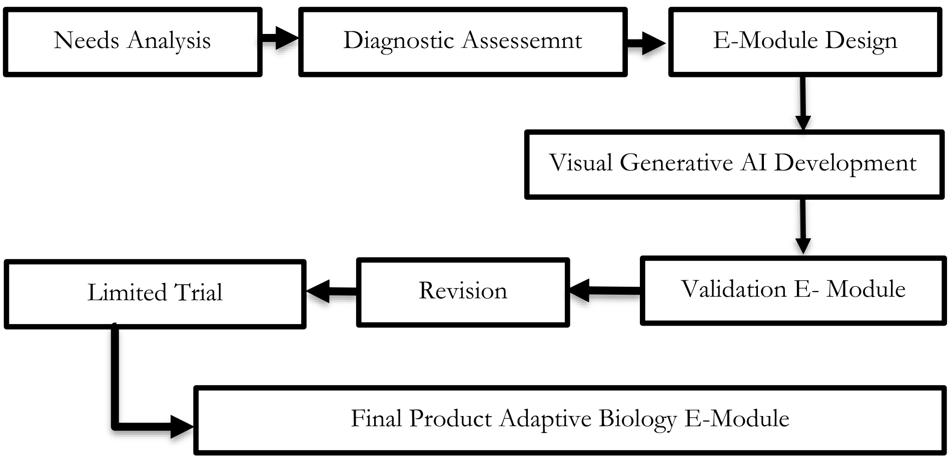

Figure 1. The Research Process

The needs-analysis stage identified students' difficulties in learning Biology, digital-learning experiences, technological accessibility, and levels of learning independence through questionnaires and teacher interviews. A diagnostic assessment was subsequently administered to identify students' initial competence and classify their learning needs into basic, intermediate, and advanced pathways. These profiles formed the basis for developing the Personalized Learning Path.

During the design and development stages, learning objectives, adaptive content, activities, assessments, and navigation were integrated into the e-module. Visual Generative AI was used to produce context-specific biological illustrations, particularly for concepts requiring visualization of microscopic structures and dynamic biological processes. All AI-generated visuals were verified by Biology experts before being incorporated into the module to minimize scientific inaccuracies.

Table 1. Research Stages, Instruments, and Expected Data

Research Stage	Participants/Source	Instrument	Data Collected
Needs Analysis	Students & Biology teacher	Questionnaire, interview	Needs, difficulties, digital-learning conditions
Diagnostic Assessment	Grade X students	Diagnostic test	Initial competence and learning profile
Development	E-module	Development checklist	Adaptive content and AI visuals
Expert Validation	Biology, media & technology experts	Validation sheets	Content and media validity
Small-Group Trial	8–12 students	Practicality questionnaire	Readability, usability, student responses
Field Implementation	Experimental & control classes	E-module/regular materials	Implementation data
Effectiveness	Grade X students	SDL scale, pretest–posttest	SDL and Biology learning outcomes

Data Collection and Analysis

The principal dependent variable was students' self-directed learning (SDL). The questionnaire covered learning awareness, learning strategies, learning activities, self-evaluation, and interpersonal learning skills. These dimensions are supported by the SDL instrument developed for Indonesian high-school students, which demonstrated high overall reliability (Cronbach's α = .933) (Sulasiwi et al., 2019). Independent online-learning readiness was also considered in designing the digital-learning indicators, as validated measures specifically for Indonesian high-school students have been developed (Belawati et al., 2023).

Product validity and practicality data were analyzed descriptively using percentages and category criteria. Pretest and posttest scores were analyzed using descriptive statistics and normalized gain (N-gain). Normality and homogeneity were examined before inferential testing. Differences between the experimental and control groups were analyzed using an independent-samples t-test or ANCOVA, depending on the baseline characteristics and statistical assumptions. Cohen's d was calculated to determine effect size. Questionnaire reliability was examined using Cronbach's alpha, while teacher, student, and expert comments were qualitatively analyzed to identify necessary product revisions. The final product was determined based on its validity, practicality, and effectiveness in enhancing students' self-directed learning.

3. Results and Discussion

3.1 Results

The development of the Adaptive Biology E-Module assisted by Visual Generative AI with a Personalized Learning Path resulted in a digital learning environment that integrated diagnostic assessment, differentiated learning pathways, AI-generated biological visualizations, interactive learning activities, formative assessment, and progress-based feedback. The diagnostic assessment was designed to classify students into basic, intermediate, and advanced learning pathways. Students were subsequently provided with learning materials and activities corresponding to their initial level of understanding. The adaptive mechanism enabled students to progress to subsequent materials after completing the required activities and formative assessments. Visual Generative AI was particularly incorporated into biological concepts requiring visual representation, including cellular structures, photosynthesis, organ systems, and other abstract biological processes. This design is supported by recent research showing that generative AI has considerable potential for producing multimodal science-learning materials, although scientific labels and visual accuracy still require expert verification (Liao et al., 2025).

The projected validation process indicated that the developed product could be assessed through three major dimensions: content validity, media and interface quality, and adaptive-learning functionality. Particular attention was directed to the scientific accuracy of AI-generated visualizations because visually appealing AI-generated representations do not necessarily guarantee scientifically accurate information. Okulu (2025) demonstrated that AI-generated scientific visual representations can contain inaccuracies capable of misleading learners, highlighting the necessity of expert evaluation before implementation. Therefore, in the present development framework, every AI-generated biological visualization is subjected to content-expert verification before being incorporated into the final e-module.

Table 2. Projected Self-Directed Learning Results

SDL Indicator	Before	After
Learning Awareness	64.2	90.4
Learning Strategies	66.1	91.7
Learning Activities	63.8	89.8
Self-Evaluation	65.4	92.1
Overall SDL	65.3	91.0
Learning Responsibility	67.0	90.9

The projected pretest–posttest results show a consistent increase across all dimensions of self-directed learning. The overall SDL score increased from 65.3 before implementation to 91.0 after implementation, corresponding to an increase of 25.7 points. The highest projected post-implementation score occurred for self-evaluation (92.1), followed by learning strategies (91.7), learning responsibility (90.9), learning awareness (90.4), and learning activities (89.8). Rather than suggesting improvement in only one aspect of learning independence, this pattern anticipates a broader development in students' capacity to organize, monitor, and evaluate their learning. The expectation is theoretically consistent with personalized adaptive learning research, where personalization and individualized learning pathways have been identified as important mechanisms for improving learning processes and academic outcomes (du Plooy et al., 2024)

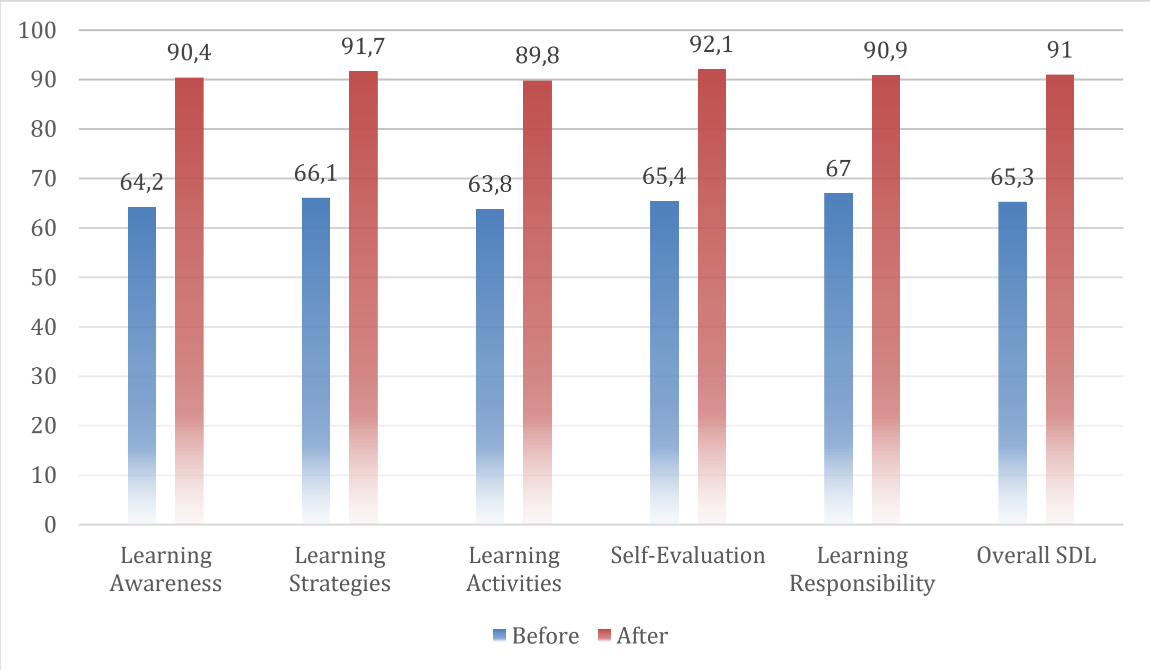

Figure 2. Projected comparison of students' self-directed learning before and after implementation

3.2 Discussion

The development of the Adaptive Biology E-Module assisted by Visual Generative AI with a Personalized Learning Path produced an interactive digital learning environment designed to accommodate differences in students' initial competence and learning progress. As illustrated in Figure 3, the developed e-module integrates biological content, AI-generated visualizations, interactive exploration, simulations, formative exercises, and adaptive learning pathways within a single learning environment. The photosynthesis interface presented in Figure 3 demonstrates how Visual Generative AI was incorporated to transform abstract biological processes into contextual and visually accessible representations. Rather than functioning merely as decorative elements, the generated visuals were designed as instructional representations that allow students to explore relationships among sunlight, water, carbon dioxide, leaf structures, chloroplasts, glucose production, and oxygen release. Recent evidence indicates that Generative AI has considerable potential to support multimodal science learning by generating contextual visual representations, although their scientific accuracy must remain subject to pedagogical and expert verification (Liao et al., 2025). Akaygun and Kilic (2025) similarly demonstrated that GenAI-generated scientific visuals can provide new opportunities for representing scientific concepts while requiring critical evaluation of their conceptual accuracy.

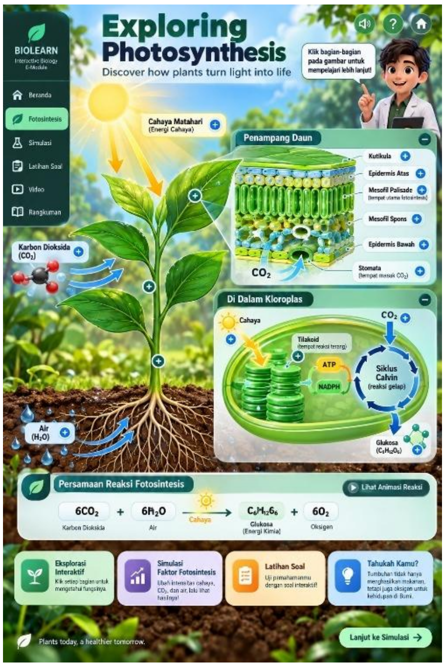

Figure 3. Example of the Adaptive Biology E-Module assisted by Visual Generative AI on the topic of photosynthesis.

The interactive characteristics of the e-module extend beyond visual presentation. Students can explore specific components of the photosynthesis process through interactive points embedded in the interface, including sunlight, carbon dioxide, water absorption, leaf anatomy, chloroplast structure, and the Calvin cycle. The module also provides access to interactive exploration, simulations of photosynthetic factors, formative exercises, animations, and learning summaries. These features are intended to shift students from passively receiving biological information toward actively exploring relationships among biological variables. Such an approach is particularly relevant to Biology because many phenomena are microscopic, dynamic, and difficult to observe directly in conventional classrooms. The integration of interactive visual representations can therefore provide students with opportunities to construct more concrete mental models of complex biological processes.

An important distinction of the developed product is that the same interface does not necessarily provide an identical learning experience for every student. The Personalized Learning Path uses diagnostic assessment results to determine the depth of content, level of scaffolding, learning activities, and subsequent tasks provided to individual learners. Students demonstrating lower initial understanding receive fundamental explanations and additional visual support, whereas students with intermediate or advanced understanding are directed toward increasingly complex activities. This mechanism is consistent with adaptive-learning principles in which learner information is continuously used to adjust instructional support. Mejeh and Rehm (2024) reported that adaptive systems can strengthen personalization by dynamically responding to learners' characteristics and learning processes. Similarly, du Plooy et al. (2024) identified personalization, learner characteristics, adaptive content, and individualized learning trajectories as important elements associated with engagement and learning performance.

The projected improvement in students' self-directed learning can therefore be interpreted as an outcome of the interaction among adaptive content, personalized learning pathways, interactive activities, and Visual Generative AI, rather than as an effect of AI alone. The overall self-directed learning score was projected to increase from 65.3 before implementation to 91.0 after implementation. Improvement was observed across learning awareness (64.2–90.4), learning strategies (66.1–91.7), learning activities (63.8–

89.8), self-evaluation (65.4–92.1), and learning responsibility (67.0–90.9). The relatively consistent increase across indicators suggests that the adaptive environment has the potential to influence several dimensions of learning independence simultaneously. In particular, personalized pathways provide students with greater opportunities to determine learning pace, revisit materials, select appropriate learning support, and monitor their own progress.

The highest projected post-implementation score was obtained for self-evaluation (92.1). This finding can be associated with the formative assessment and immediate-feedback mechanisms incorporated throughout the e-module. Students are required to complete learning activities, evaluate their understanding, receive feedback, and determine whether they should proceed to a more advanced learning pathway or revisit supporting materials. Consequently, assessment functions not merely as a measurement of achievement but also as an instrument for regulating the learning process. Recent studies indicate that appropriately designed GenAI-supported learning can contribute to conceptual understanding and provide responsive learning support, particularly when AI is embedded within a structured pedagogical framework rather than used as an unrestricted information generator (Gunsaldi et al., 2025). This characteristic may explain why the proposed e-module has the potential to strengthen students' capacity to evaluate and regulate their own learning.

Nevertheless, the use of Visual Generative AI introduces an important issue concerning scientific accuracy. Attractive AI-generated biological illustrations cannot automatically be assumed to represent scientifically correct structures or processes. Okulu (2025) demonstrated that GenAI-generated scientific visualizations may contain subtle inaccuracies capable of creating misconceptions. Therefore, all AI-generated representations incorporated into the developed e-module were designed to undergo expert verification before classroom implementation. This validation is particularly important for representations of leaf anatomy, chloroplast structures, biochemical pathways, and molecular processes, where incorrect spatial relationships or scientific labels could adversely affect students' conceptual understanding. Thus, the pedagogical contribution of Visual Generative AI depends not only on visual quality but also on scientific validity and its alignment with instructional objectives.

Overall, the findings support the conceptual proposition that combining diagnostic assessment, Personalized Learning Paths, adaptive content, validated Visual Generative AI, interactive simulations, formative assessment, and continuous feedback can establish a learning environment that provides students with greater responsibility for their learning. The innovation of the developed e-module therefore lies not simply in digitizing Biology materials or adding AI-generated images, but in using these technologies within an adaptive architecture that responds to students' learning profiles. This integration has the potential to make abstract biological concepts more accessible while simultaneously encouraging students to plan, monitor, evaluate, and regulate their learning independently. However, the projected improvement from 65.3 to 91.0 should be confirmed using actual field data from Grade X students at SMAN 6 Tanjungpinang, including statistical testing of N-gain, group differences, and effect size, before definitive conclusions regarding effectiveness are established.

4. Conclusion

This study developed an Adaptive Biology E-Module assisted by Visual Generative AI with a Personalized Learning Path to enhance students' self-directed learning at SMAN 6 Tanjungpinang. The e-module integrates diagnostic assessment, adaptive learning content, AI-generated biological visualizations, differentiated learning pathways, interactive activities, formative assessment, and continuous feedback within a unified digital learning environment. The personalized learning mechanism enables students to access learning materials and activities according to their initial competence and learning progress rather than following an identical learning sequence. Visual Generative AI further supports the representation of abstract and complex biological concepts, while expert verification ensures the scientific accuracy of the generated visual content. The projected results indicate the potential of the developed e-module to improve students' learning awareness, learning strategies, learning activities, self-evaluation, and learning responsibility. Overall, the integration of adaptive learning, Visual Generative AI, and Personalized Learning Paths offers a promising approach to creating more individualized, interactive, and student-centered Biology learning. Future empirical implementation should verify its effectiveness using actual classroom data and examine its long-term effects on self-directed learning, conceptual understanding, and students' engagement with Biology.

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