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Development of artificial intelligence-based interactive learning media to enhance students' critical thinking skills

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Abstract. The rapid advancement of Artificial Intelligence (AI) has significantly transformed educational practices. In biology education, many concepts remain abstract and difficult to understand through conventional instruction, leading to low conceptual understanding and inadequate critical thinking skills among students. Therefore, this study aimed to develop an Artificial Intelligence-based interactive learning media and evaluate its validity, practicality, and effectiveness in enhancing senior high school students' critical thinking skills in biology learning. This research employed the Research and Development (R&D) method using the ADDIE instructional design model, consisting of Analysis, Design, Development, Implementation, and Evaluation stages. The participants included biology education experts, instructional media experts, biology teachers, and Grade XI students. The research instruments consisted of expert validation sheets, teacher and student practicality questionnaires, observation sheets, and critical thinking tests. Data were analyzed using descriptive statistics, Aiken's V, Cronbach's Alpha, normalized gain (N-Gain), paired-sample t-test, and Cohen's d effect size. The developed media integrates AI-assisted tutoring, adaptive quizzes, animated biological simulations, virtual laboratory activities, personalized feedback, and learning analytics. Expert validation results indicated that the media achieved a very high level of validity (94.2%). Practicality evaluation showed positive responses from both teachers (93.7%) and students (89.3%), indicating that the media was highly practical for classroom implementation. Furthermore, the effectiveness test showed significant improvement in students' critical thinking skills, with an average N-Gain score of 0.72, categorized as great improvement. Statistical analysis confirmed significant differences between pre-test and post-test scores ($p < 0.001$) with a large effect size. The findings suggest that integrating Artificial Intelligence into biology learning media provides meaningful learning experiences by facilitating personalized instruction, immediate feedback, and interactive visualization of complex biological concepts. Consequently, AI-based interactive learning media can serve as an effective educational innovation to improve biology learning outcomes and foster higher-order thinking skills.
Keywords: Artificial intelligence, Biology learning, Critical thinking Skills, Interactive media.

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INTRODUCTION

Biology is a fundamental branch of science that explains living organisms and their interactions with the environment through observation, experimentation, and scientific reasoning. As one of the core science subjects in secondary education, biology plays a vital role in developing scientific literacy, problem-solving abilities, and critical thinking skills among students (Zhou et al., 2025). However, biology also contains numerous abstract concepts that are difficult for learners to visualize directly, including cellular metabolism, genetic inheritance, molecular interactions, enzyme mechanisms, ecological relationships, and physiological processes. These abstract characteristics often create misconceptions and reduce students' motivation to learn when instruction relies solely on conventional teaching methods (Goodrich et al., 2021).

In this study, AI refers specifically to a conversational AI-based virtual tutor (AI Tutor) integrated into an interactive learning media. The AI Tutor functions as an intelligent learning assistant that allows students to interact with learning materials through questions and

responses. Rather than simply presenting information, the AI Tutor provides explanations, guiding questions, feedback, and prompts that encourage students to examine problems and formulate their own reasoning. This conversational interaction is particularly relevant to developing critical thinking because students are encouraged to explain their ideas, identify relationships between concepts, consider alternative answers, and justify their conclusions (Rizos & Zambianchi, 2025).

Critical thinking is an essential competency in contemporary education because students need to evaluate information, analyze problems, interpret evidence, make logical inferences, and provide reasoned conclusions. Nevertheless, conventional digital learning media often emphasize information delivery and objective-based exercises rather than providing opportunities for students to actively analyze and evaluate information. As a result, students may interact with learning materials at a superficial level without sufficiently engaging in higher-order thinking processes. Learning media therefore need to provide not only attractive content but also learning experiences that actively stimulate analysis, evaluation, inference, and reasoning (Hadinejad et al., 2025).

Traditional biology instruction in many schools continues to emphasize teacher-centered learning through lectures and textbook-based explanations. Although this approach effectively delivers factual knowledge, it often limits students' opportunities to construct understanding through exploration and inquiry actively (Irawan et al., 2025). Several studies have reported that passive learning environments contribute to low conceptual understanding and insufficient development of higher-order thinking skills, particularly critical thinking, which is one of the essential competencies required in twenty-first-century education (Irawan, 2023)

The rapid advancement of digital technology has introduced various innovative instructional media designed to improve learning effectiveness. Interactive multimedia, virtual laboratories, augmented reality, and simulation-based learning environments have been widely implemented in biology education to visualize microscopic structures and biological processes that cannot be directly observed in classroom settings. Such technologies have demonstrated positive impacts on students' conceptual understanding, motivation, and engagement. Nevertheless, most existing digital learning media remain static and primarily function as presentation tools without adapting to individual students' learning characteristics (Rastgoo et al., 2024).

Artificial Intelligence (AI) has recently emerged as one of the most promising educational technologies capable of transforming conventional digital learning environments into intelligent learning systems. AI enables educational media to provide adaptive learning pathways, personalized recommendations, automated assessment, intelligent tutoring, immediate feedback, and predictive learning analytics. These capabilities allow learning systems to respond dynamically to students' individual needs, thereby supporting more meaningful and efficient learning experiences (Weidlich et al., 2025).

The AI Tutor developed in this study is designed to address this limitation through interactive question-and-response interactions. When students encounter a problem, the AI Tutor does not merely provide the correct answer but can provide explanations and guiding prompts that direct students to reconsider their reasoning. For example, students may be asked to identify the cause of a phenomenon, compare alternative explanations, interpret experimental results, or explain why they chose a particular answer. Through this process, students are encouraged to move from simply receiving information toward actively processing and evaluating information. The conversational nature of the AI Tutor therefore becomes an important component that distinguishes the developed media from conventional digital learning materials (Rizos & Zambianchi, 2025).

Several previous studies have demonstrated the effectiveness of digital learning media in improving biology learning outcomes. Interactive multimedia has been shown to enhance conceptual understanding and increase student motivation through visual representations of complex biological systems. Virtual laboratory applications enable students to conduct experiments safely and repeatedly without the limitations of physical laboratory facilities. Likewise, augmented reality technologies facilitate three-dimensional visualization of biological structures, promoting deeper understanding of anatomical and physiological concepts (Hosny et al., 2025).

Despite these advancements, relatively few studies have integrated Artificial Intelligence comprehensively into biology learning media. Existing AI applications in education generally focus on automated grading systems, chatbots, or recommendation engines without combining adaptive instruction, interactive simulations, virtual experimentation, and intelligent tutoring into a unified biology learning platform. Consequently, there remains a significant research gap concerning the development of AI-based biology learning media capable of simultaneously improving conceptual understanding and critical thinking skills (Irawan et al., 2023).

Critical thinking has become one of the most important competencies in modern education. According to widely accepted educational frameworks, critical thinking involves the ability to analyze information, evaluate evidence, formulate logical arguments, draw conclusions based on scientific reasoning, and solve complex problems systematically. In biology learning, these competencies are essential because biological phenomena often involve multifactorial relationships requiring analytical reasoning rather than simple memorization (Velásquez-C et al., 2024)

Unfortunately, international educational assessments consistently indicate that many students still struggle to apply critical thinking skills to scientific problems. Students frequently rely on rote memorization instead of conceptual reasoning, resulting in limited ability to transfer knowledge into real-world contexts. This situation highlights the urgent need for innovative instructional strategies capable of facilitating inquiry-based and student-centered learning (Weijsenfeld & Sarmah, 2025)

The emergence of AI technologies provides an opportunity to redesign biology instruction by creating intelligent learning environments that actively support students' cognitive development. AI can analyze students' responses in real time, identify misconceptions, generate adaptive questions, recommend individualized learning materials, and provide immediate formative feedback. These characteristics are expected to encourage active engagement, reflective thinking, and self-regulated learning (Opoku-Acheampong et al., 2024) Moreover, integrating AI into biology education aligns with current educational transformation initiatives emphasizing digital literacy, personalized learning, and Education 5.0. Schools are increasingly encouraged to utilize intelligent technologies not merely as supplementary tools but as integral components of teaching and learning processes that foster creativity, collaboration, communication, and critical thinking (Kong et al., 2024)

Based on the aforementioned issues, this study develops an Artificial Intelligence-based interactive learning media specifically designed for senior high school biology learning using the ADDIE instructional design model. The developed media integrates AI tutoring, adaptive assessment, biological simulations, virtual laboratory activities, personalized feedback, and learning analytics within a single learning platform.

METHOD

This study employed a Research and Development (R&D) approach using the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. The study aimed to develop an Artificial Intelligence (AI)-based interactive

learning media for senior high school biology learning and evaluate its validity, practicality, and effectiveness.

The research was conducted at a public senior high school involving 36 Grade XI students, two biology education experts, two educational technology experts, and two biology teachers. The experts evaluated the content and media design, while teachers and students participated in the practicality and effectiveness testing.

During the analysis stage, the team identified curriculum requirements, students' learning needs, and existing instructional problems through interviews, classroom observations, and document analysis. In the design stage, the team designed the learning objectives, instructional flow, user interface, and AI-assisted learning features. The development stage involved creating interactive learning media and integrating AI-based tutoring, biological simulations, adaptive quizzes, virtual laboratory activities, and automatic feedback. The product was then revised based on expert suggestions. During the implementation stage, the media was used in biology learning activities, and the evaluation stage assessed the product's quality and effectiveness.

The research instruments included expert validation sheets, teacher and student practicality questionnaires, and a critical thinking test administered before and after the implementation. Content validity was assessed using Aiken's V, while instrument reliability was examined using Cronbach's Alpha.

The collected data were analyzed using descriptive statistics to determine the media's validity and practicality. Students' learning improvement was measured using the normalized gain (N-Gain). At the same time, the significance of differences between pre-test and post-test scores was analyzed using a paired-sample *t*-test with a significance level of 0.05. All statistical analyses were performed using IBM SPSS Statistics.

RESULTS AND DISCUSSION

Results

The AI-based interactive learning media was successfully developed using the ADDIE model. The media integrates AI-assisted explanations, interactive simulations, adaptive quizzes, and automatic feedback to support biology learning. These features encourage active learning and improve students' critical thinking skills.

The expert validation results indicated that the developed media was highly valid, with an average score of 94.2%. The content aspect received the highest score (95.2%), while the language aspect received the lowest score (93.4%). Overall, the product was considered appropriate for classroom implementation after minor revisions, as shown in Table 1.

Table 1. Expert Validation Results

Aspect	Score (%)	Category
Content	95.2	Very Valid
Media Design	94.5	Very Valid
Language	93.4	Very Valid
Average	**94.2**	**Very Valid**

The high validation score indicates that the developed media met the requirements for content accuracy, instructional design, and usability. Interactive simulations and AI-assisted explanations provide visual, adaptive learning experiences that help students understand abstract biological concepts more effectively.

The practicality evaluation also showed positive responses from teachers and students. Teachers rated the media at 93.7%, while students gave an average score of 89.3%, indicating that the media was easy to use and supported the learning process. Students reported that the AI-assisted explanations and interactive features made learning more engaging and helped

them understand biological concepts more easily. The results of the effectiveness test are shown in Table 2.

Table 2. Students' Learning Outcomes

Variable	Result
Pre-test Mean	58.41
Post-test Mean	86.75
N-Gain	0.72 (High)
p-value	<0.001

The improvement in students' critical thinking skills suggests that the AI-based learning media effectively supported meaningful learning. Personalized feedback and adaptive quizzes enabled students to identify misconceptions and receive immediate guidance, while interactive simulations helped them visualize complex biological processes. These findings are consistent with previous studies reporting that AI-supported learning environments can enhance student engagement, conceptual understanding, and higher-order thinking skills. Overall, the findings demonstrate that the developed AI-based interactive learning media is valid, practical, and effective for biology learning.

The effectiveness of the developed media was evaluated through pre-test and post-test assessments of students' critical thinking skills. As presented in Table 2, the mean score increased from 58.41 on the pre-test to 86.75 on the post-test, with an N-Gain value of 0.72, indicating a high level of learning improvement. The paired sample *t*-test also revealed a significant difference between the pre-test and post-test scores ($p < 0.001$).

The effectiveness of the developed media was evaluated through pre-test and post-test assessments of students' critical thinking skills. The learning process was conducted using the developed AI-based interactive learning media through several stages. At the beginning of the learning session, students completed a pre-test to determine their initial level of critical thinking. Students then accessed the learning materials through the interactive media, which integrated several features, including an AI-based conversational tutor (AI Tutor), interactive simulations, virtual laboratory activities, and adaptive quizzes. The AI Tutor was integrated directly into the learning activities and functioned as an interactive learning assistant. Students could ask questions related to the learning content, request explanations, and receive guiding feedback from the AI Tutor. Rather than only providing direct answers, the AI Tutor encouraged students to analyze problems, consider alternative explanations, provide reasons for their answers, and draw conclusions.

Discussion

The improvement in students' critical thinking skills can be explained by the specific learning activities embedded in the developed AI-based interactive learning media. As shown in Figure 1, the media integrates five main components: Interactive Simulation, Virtual Laboratory, Adaptive Quiz, AI Tutor, and Learning Analytics. Each component was designed to engage students in different cognitive activities, including interpreting information, analyzing problems, evaluating evidence, drawing conclusions, and reflecting on their learning. Therefore, the developed media's contribution to critical thinking skills does not simply result from the use of artificial intelligence, but from how its features provide opportunities for students to process and evaluate information actively.

The Interactive Simulation is one of the main features that facilitates analytical thinking. In this feature, students can explore the stages of the human digestive process, such as the mouth, esophagus, stomach, small intestine, and large intestine, through an interactive visual representation. Students are not only presented with static information but can observe

the sequence and relationships among different stages of the digestive process (Velásquez-C et al., 2024)

This allows students to examine how one process relates to another and to identify relationships between biological structures and their functions. Such activities require students to interpret information and analyze relationships, which are important components of critical thinking. The interactive nature of the simulation also allows students to learn through exploration rather than simply memorizing the sequence of digestive organs (Hosny et al., 2025)

The Virtual Laboratory provides a more direct opportunity for students to engage in evidence-based reasoning. As illustrated in Figure 1, students can conduct a virtual experiment involving amylase, starch, and water and observe the resulting changes. Students must consider the experimental variables, observe the results, and interpret the relationship between the substances involved and the observed outcome. For example, when students observe that starch changes after adding amylase, they need to connect the observation to the enzyme's biological function. This process encourages students to analyze evidence, interpret experimental results, and formulate conclusions based on observations. Thus, the Virtual Laboratory provides a learning context in which students practice scientific reasoning rather than merely receiving predetermined explanations (Degen, 2025)

The Adaptive Quiz further supports critical thinking by presenting questions that require students to select and justify appropriate answers based on the learning content. For example, the question shown in Figure 1 asks students to determine which substance activates pepsinogen in the stomach. To answer correctly, students need to recall relevant concepts, distinguish among possible alternatives, and evaluate which answer is logically consistent with the physiological process. The adaptive nature of the quiz also gives students opportunities to encounter different levels of questions based on their performance. Immediate feedback enables students to recognize incorrect reasoning and reconsider their responses. Therefore, the Adaptive Quiz functions not only as an assessment tool but also as a mechanism for repeated practice in analysis, evaluation, and decision-making, as shown in Figure 1.

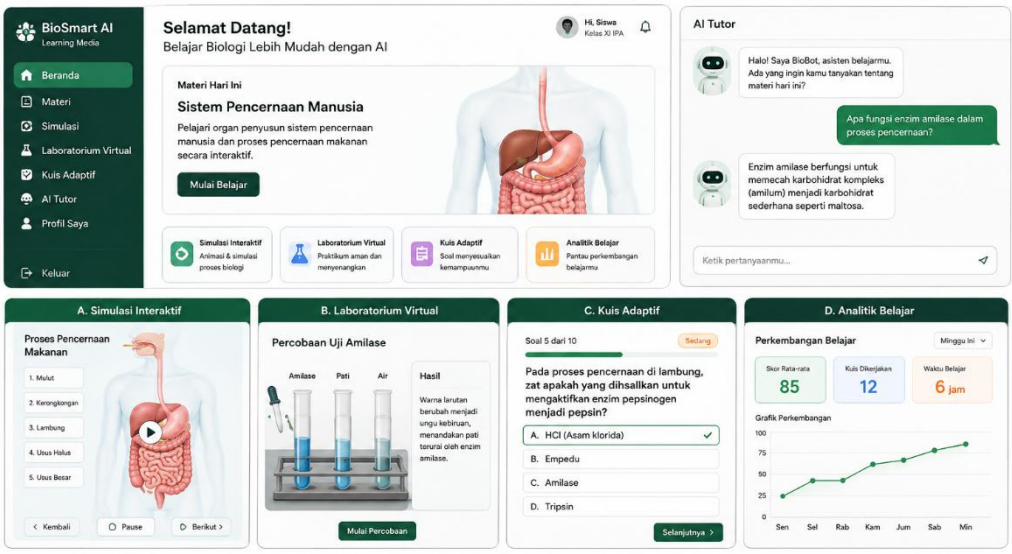

Figure 1. Display of the AI-based Interactive Learning Media Developed

The AI Tutor represents the component that most directly supports interactive questioning and cognitive scaffolding. As shown in Figure 1, students can ask questions related to the learning material and receive responses from the AI Tutor. Importantly, this feature can support critical thinking when the interaction encourages students to understand the reasons behind an answer rather than simply providing the correct answer (Curi et al., 2025).

Through question-and-response interactions, students can clarify concepts, examine explanations, and reconsider their initial understanding. The AI Tutor therefore provides an opportunity for students to engage in dialogic learning, in which questions and explanations can stimulate further reasoning and conceptual examination. Its role is consequently not limited to delivering information but can function as a cognitive support mechanism during the learning process (Huwer et al., 2025).

The Learning Analytics feature supports the reflective dimension of critical thinking. The dashboard provides information regarding students' scores, completed quizzes, learning duration, and progress over time. This information enables students to identify their strengths and areas that still require improvement. For example, students can review their learning progress and recognize whether their performance is improving or whether additional learning activities are necessary. Such monitoring encourages students to reflect on their own learning performance and make decisions about subsequent learning strategies. This process is related to self-regulation, which is an important component of higher-order thinking and critical thinking (Schmidt et al., 2025)

The integration of these five components creates a learning cycle that continuously engages students in higher-order cognitive activities. The Interactive Simulation encourages students to explore and analyze processes; the Virtual Laboratory requires them to examine evidence and draw conclusions; the Adaptive Quiz provides opportunities to evaluate alternatives and make decisions; the AI Tutor facilitates questioning, explanation, and conceptual clarification; while Learning Analytics enables students to monitor and reflect on their learning progress. Consequently, the features are complementary rather than functioning as independent technological components (Irawan & Hernita, 2025)

The present finding is particularly relevant to biology learning because students in ordinary classroom settings cannot directly observe many biological processes. Therefore, animations, diagrams, simulations, and interactive representations can make abstract processes more concrete and understandable. In contrast to conventional media that primarily present static text and images, the developed media provides opportunities for students to interact with biological phenomena actively. Thus, the high validity score suggests that the media was not only technically acceptable but also pedagogically aligned with the characteristics of biology learning (Zahra et al., 2021)

Therefore, the AI Tutor's contribution in this study is not simply its ability to answer students' questions. More importantly, the feature creates an additional learning support mechanism that allows students to obtain explanations at the point of difficulty (Fonseca et al., 2025). This condition can encourage independent learning and potentially increase students' confidence in engaging with difficult biology concepts. Previous research provide information that the role of the AI Tutor should remain complementary to teacher guidance, particularly because AI-generated explanations require appropriate instructional control and verification (Wang et al., 2024).

Another important feature is the Interactive Simulation, which dynamically visualizes biological processes. For example, students can observe the sequence of the human digestive process through animations (Hosny et al., 2025). This visualization helps students understand processes that are difficult to observe directly through conventional classroom instruction. The finding supports the multimedia learning perspective that relevant combinations of verbal explanations and visual representations can facilitate the construction of mental models (Mashroofa et al., 2023). The interactive nature of the simulation further distinguishes the developed media from conventional multimedia because students are not only observing representations but can interact with learning content and explore biological processes (Gita et al., 2025)

The Interactive Simulation therefore has the potential to reduce students' dependence on memorization. Instead of merely remembering the sequence of the digestive system, students can observe the relationships between organs and processes (Irawan et al., 2025) This is particularly important for developing higher-order thinking because students need to connect biological structures, processes, and functions. In this respect, the present study extends the use of multimedia learning from simple visualization toward interactive exploration (Irawan et al., 2026)

The Virtual Laboratory also provides significant educational value. Laboratory activities are essential components of biology education because they give students opportunities to observe phenomena, formulate explanations, interpret evidence, and develop scientific reasoning. However, limitations in laboratory facilities, equipment, materials, time, and safety may restrict students' opportunities to conduct practical activities. The developed Virtual Laboratory provides an alternative environment in which students can perform simulated experiments safely and repeatedly (Suciari et al., 2021)

Compared with these previous studies, the present research provides a broader integration of the virtual laboratory with other AI-supported learning components. Previous studies generally focused on the use of virtual laboratories as the primary intervention, whereas the present media combines the Virtual Laboratory with AI tutoring, interactive simulation, adaptive assessment, and learning analytics (Irawan et al., 2025)

Consequently, the present study contributes by integrating several complementary technologies within a single instructional environment. The Virtual Laboratory provides experiential learning, the AI Tutor provides personalized assistance, the Adaptive Quiz provides differentiated assessment, and Learning Analytics provides information about learning progress. This integrated design may explain why the developed media produced improvements not only in students' learning experience but also in critical thinking performance.

The Adaptive Quiz represents another important component of the developed media. The system adjusts question difficulty according to students' performance, allowing students to receive learning tasks that match their current level of understanding. This mechanism aligns with personalized and adaptive learning, in which instructional content and assessment are adjusted to individual learner characteristics and performance. Recent reviews of AI-based personalized learning emphasize the importance of student modeling, assessment data, and personalized recommendations in creating learning experiences that respond to individual needs (Irawan & Hernita, 2025)

This finding provides an important qualification to the present results. The contribution of the Learning Analytics Dashboard should not be understood as an independent cause of improved learning outcomes. Rather, its value lies in providing actionable information that teachers and students can use to identify learning difficulties, monitor progress, and determine subsequent learning activities. In the context of the present media, learning analytics becomes more meaningful because it is connected with the AI Tutor and Adaptive Quiz. In other words, the dashboard is part of an integrated learning ecosystem rather than an isolated reporting tool (Al-kfairy et al., 2025).

The findings also extend previous research by demonstrating the potential of integrating multiple AI-supported and interactive learning functions into a single biology learning environment. Previous studies have generally examined individual technological components, such as virtual laboratories, AI-supported personalized learning, or adaptive systems. In contrast, the present study combines AI tutoring, interactive simulation, virtual experimentation, adaptive assessment, and learning analytics. This integration provides a more comprehensive learning environment in which students can obtain personalized assistance,

visualize abstract concepts, conduct simulated investigations, practice through differentiated questions, and monitor their learning progress (Fonseca et al., 2025).

Therefore, the effectiveness of the developed media can be understood as the result of the interaction among its different components rather than the effect of a single technological feature. The AI Tutor provides immediate personalized support; Interactive Simulation facilitates conceptual visualization; the Virtual Laboratory provides opportunities for inquiry and experimentation; the Adaptive Quiz adjusts cognitive demands according to student performance; and Learning Analytics supports reflection and instructional decision-making. Together, these features create a student-centered learning environment that supports active participation and higher-order thinking.

Despite these positive findings, implementing AI-based learning media should still be accompanied by appropriate teacher supervision. AI should function as a learning support system rather than a substitute for teacher interaction. This consideration matters because recent research on AI-supported personalized learning has identified potential gaps in cognitive engagement, collaboration, and broader educational competencies that cannot be addressed solely through technological personalization. Consequently, future implementation should position AI as a complementary component within teacher-guided learning. Further research is also needed to examine the effectiveness of the media using larger samples, control or comparison groups, longer intervention periods, and analysis of individual features to determine which components contribute most strongly to students' critical thinking development.

CONCLUSION

AI-based interactive learning media is valid, practical, and effective for biology learning. The integration of AI-assisted tutoring, interactive simulations, virtual laboratory activities, adaptive assessment, and learning analytics provides a more interactive and personalized learning environment than conventional instructional media. The substantial increase in students' critical thinking scores further suggests that the media has the potential not only to improve conceptual understanding but also to support higher-order cognitive development, and further research should also investigate the specific contribution of each feature of the media, including the Interactive Simulation, Virtual Laboratory, Adaptive Quiz, AI Tutor, and Learning Analytics. A comparative or factorial research design could be employed to determine which features contribute most significantly to particular dimensions of critical thinking, such as analysis, evaluation, inference, explanation, and self-regulation.

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