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AI-CBL: A Technology-Enhanced Learning Model Combining Chatbot and Case-Based Pedagogy to Improve Critical Thinking in Physics Education

Halimah Al Hasanah[1,a)], Bambang Heru Iswanto[2,b)], Iwan Sugihartono[2,c)]

[1]*Master's Program of Physics Education, Universitas Negeri Jakarta, Jalan Rawamangun Muka, Jakarta Timur, 13220, Indonesia*
[2]*Department of Physics, Universitas Negeri Jakarta, Jalan Rawamangun Muka, Jakarta Timur, 13220, Indonesia*

✉: [a)]halimahalhasanah@gmail.com, [b)]bhi@unj.ac.id, [c)]iwan-sugihartono@unj.ac.id

Abstract

In response to the pedagogical challenges of traditional physics education and the evolving demands of Education 4.0, this study introduces the AI-CBL model, a hybrid instructional approach integrating Case-Based Learning with an AI-powered chatbot. The research aimed to develop and evaluate the effectiveness of the AI-CBL model in enhancing critical thinking among undergraduate physics students. Employing Research and Development (R&D) within a pretest-posttest control group design framework, the AI-CBL model was implemented through an interactive e-learning platform across two sessions on the topic of electromagnetic induction. Seventy students were divided into two groups: a control group (CBL only) and an experimental group (AI-CBL). Data collection instruments included pre- and post-tests, expert validation sheets, observation protocols, and questionnaires. Expert validation results showed high feasibility (average score of 4.25). The AI-CBL group demonstrated significantly higher critical thinking gains (N-Gain = 0.9838, categorized as High) compared to the control group (N-Gain = 0.5212, categorized as Medium), with a t-test indicating a significant difference ($p < 0.001$). These results highlight the pedagogical effectiveness of the AI-CBL model in promoting deeper conceptual understanding and critical thinking. Additionally, students reported high levels of engagement, ease of use, and satisfaction with the AI chatbot's interactive features. The study confirms that the AI-CBL model provides a viable, adaptive, and impactful approach to modern physics education, promoting deeper conceptual understanding and fostering 21st-century skills.

Keywords: physics education, case-based learning, artificial intelligence chatbot, critical thinking, technology-enhanced learning

INTRODUCTION

The rapid advancement of technology in the 21st century has transformed various facets of life, including the educational sector. Within this framework, the emergence of Education 4.0 demands a radical shift in the pedagogical paradigms and instructional practices traditionally used in science education. Physics education, in particular, is expected to go beyond mere conceptual comprehension by nurturing essential 21st-century skills such as critical thinking, digital literacy, collaborative competencies, and adaptive readiness to cope with the dynamically evolving global landscape (Shenkoya & Kim, 2023; Defianti et al., 2025). Critical thinking, in particular, is emphasized within global frameworks, including the Sustainable Development Goals (SDG 4 and SDG 10), as a foundation for effective problem-solving and informed decision-making in complex, real-world contexts (Borovský et al., 2024).

In the context of physics learning, critical thinking facilitates the deep comprehension of scientific concepts, enables connections between theory and real-life phenomena, and supports reflective responses to technological progress (Muhammad et al., 2024). However, most instructional approaches in both secondary and higher education remain rooted in traditional methods, heavily reliant on lectures and routine exercises (Arend et al., 2023; Hasanah et al., 2024). These conventional models often fall short in offering students opportunities for conceptual exploration, reflective discourse, and contextual analysis through case study applications. Consequently, the development of students' critical thinking skills is often suboptimal, impairing their ability to apply physics concepts in meaningful and practical ways.

One of the fundamental challenges in physics education is the scarcity of learning strategies that are explicitly designed to independently and systematically develop critical thinking skills (Samba et al., 2020). Limited student interaction, lack of engaging learning media, and insufficient real-world case exposure exacerbate the problem (Koehler, 2022). The critical thinking skills of students and prospective science teachers are still low, so that learning is needed that explicitly trains aspects of critical thinking (Neswary et al., 2023; Siswanto et al., 2021). To address these challenges, innovative instructional strategies integrating active learning and technological support are urgently needed.

Case-Based Learning (CBL) has emerged as a pedagogical approach that responds effectively to these educational demands. CBL involves students learning through the detailed examination and resolution of real-world scenarios (Egonsdotter & Bengtsson, 2023; Taesotikul, 2023). As an active learning method rooted in constructivist theory, CBL promotes critical analysis, problem-solving, and the application of theoretical knowledge in practical situations across various disciplines (Jiang et al., 2025; Lavi & Marti, 2023; Ma & Zhou, 2022). Typical phases of CBL include case analysis, identification of core issues, discussion, solution development, and reflection. These phases provide a structured yet flexible learning process that supports both independent and collaborative engagement with complex issues.

Despite its proven benefits, the successful implementation of CBL is often hindered by several factors. These include the extended time required for case exploration, the difficulty students face in locating relevant and meaningful cases, and their limited experience in applying theoretical knowledge to real-life contexts (Dewi & Rahayu, 2023).

On the other hand, Recent developments in Artificial Intelligence (AI) have introduced new possibilities for supporting self-directed learning through chatbots. These AI tools offer personalized feedback, guided prompts, and adaptive pathways to support student autonomy and reflective learning (Virkus et al., 2024; Tapalova & Zhiyenbayeva, 2022; Wang et al., 2024). Studies show that chatbots enhance student engagement and critical thinking outcomes when integrated with instructional activities (Fabio et al., 2025). Furthermore, AI-based explanatory tools contribute to increased situational interest, positive emotions, self-efficacy, and reduced cognitive load (Lademann et al., 2025). These findings suggest that AI chatbots can provide effective scaffolding for students in autonomous learning environments and improve their cognitive outcomes (Duy et al., 2024).

The collective evidence from these studies highlights the promising potential of integrating CBL and AI chatbots to create an enriched learning environment in physics education. However, the existing body of research has mostly examined CBL and AI as separate strategies. Few empirical studies have systematically explored how these two pedagogical innovations can be synergistically combined within a single, coherent instructional model. More specifically, there remains a significant gap in the literature concerning the design, implementation, and evaluation of AI chatbot-integrated CBL platforms tailored to enhance critical thinking in physics education.

In response to this research gap, the present study introduces and evaluates an innovative instructional model named AI-CBL (Case-Based Learning with Interactive Artificial Intelligence Chatbot). This model represents a convergence of Technology-Enhanced Learning (TEL) and Case-Based Learning. TEL emphasizes the use of technology to enrich learning experiences, while CBL engages students in authentic problem-solving, the AI chatbot enhances the learning process by providing scaffolded guidance, real-time feedback, and interactive prompts that support reflective and autonomous learning (Ukenova & Bekmanova, 2023).

The AI-CBL model is designed not only to improve critical thinking in physics education but also to provide an adaptive, scalable, and technology-driven solution aligned with students' learning needs. The novelty of this study lies in its integrated approach to embedding AI chatbot technology within a CBL framework in a single, unified learning platform.

By combining the contextual richness of CBL with the adaptability and interactivity of AI technologies, the AI-CBL model addresses the pedagogical limitations of conventional physics instruction while capitalizing on digital tools to foster deeper engagement and critical inquiry. Ultimately, this study contributes to the growing field of educational technology by providing a replicable and empirically tested model that supports meaningful, flexible, and learner-centered physics education in the digital era.

METHODS

Research Design

This study employed a Research and Development (R&D) approach aimed at designing, developing, and empirically testing the effectiveness of the AI-CBL (Case-Based Learning with Interactive Artificial Intelligence Chatbot) instructional model. The primary goal of the AI-CBL model is to enhance students' critical thinking skills in the context of introductory physics education. The development process adopted the ADDIE mode comprising five phases: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). This systematic framework ensured the iterative refinement of the instructional design and its alignment with learning objectives and student needs.

The adoption of R&D methodology allowed for a comprehensive investigation of the instructional model's theoretical foundations, technological integration, practical implementation, and empirical validation. This methodological framework was selected to ensure that the AI-CBL model could be systematically developed, tested in authentic educational settings, and potentially replicated for broader application in physics and other STEM disciplines.

Participants and Sampling

The participants of this study were undergraduate students enrolled in the Physics Education program at Universitas Negeri Jakarta, who were undertaking the course on Basic Physics. A total of 70 students participated, and they were randomly assigned to two groups: 35 students in the experimental group and 35 in the control group.

The experimental group engaged in learning activities through the AI-CBL model using a web-based learning platform integrated with an AI chatbot. The control group, on the other hand, received instruction using the conventional CBL approach without technological support. The instructional intervention spanned two course sessions, with electromagnetic induction as the core topic. This content was chosen for its conceptual complexity and potential for application in real-world case scenarios.

Learning Model Development

The development of the AI-CBL model was guided by constructivist learning theory and the principles of Technology-Enabled Learning (TEL). The design focused on promoting active, contextual, and participatory learning experiences. The learning platform was built as a dynamic, web-based system allowing online access to instructional content, AI chatbot interaction, and formative assessment tools.

The learning process in AI-CBL was structured into four phases: (1) Case Identification and Analysis, (2) Case Discussion, (3) Case Resolution, and (4) Evaluation and Reflection. In each phase, students engaged with contextual physics cases and were encouraged to use the AI chatbot as a reflective and exploratory tool. The chatbot, powered by ChatGPT, offered guided prompts, automatic feedback, and problem-solving suggestions.

The AI-CBL Learning Platform was equipped with interactive features including an AI chatbot, case progression workspace, and topic-specific modules. The system was designed with a user-friendly interface and included a back-end database for tracking user activity and learning analytics. The integration of the chatbot was facilitated through secure API token access, allowing seamless interaction within the e-learning environment.

Instruments and Data Collection

A variety of validated instruments were employed for data collection in this study. These included:

1. Needs Analysis Questionnaire: Used to identify student and instructor perspectives regarding challenges in learning physics and expectations for innovative learning tools.
2. Expert Validation Sheets: Employed to evaluate the design feasibility, content relevance, and pedagogical effectiveness of the AI-CBL model. Validators included experts in educational technology and physics instruction.
3. Pre-test and Post-test Instruments: Developed to assess changes in students' conceptual understanding and critical thinking skills before and after the instructional intervention. Instruments included Open-ended critical thinking questions aligned to five critical thinking indicators.
4. Media Evaluation Questionnaire: Gathered student feedback on the usability, interactivity, and effectiveness of the AI-CBL platform.
5. Observation and Interview Guides: Used to triangulate findings and explore students' experiences, difficulties, and perceptions related to the AI-CBL implementation.

All instruments underwent theoretical validation by being reviewed and approved by academic advisors to ensure their appropriateness and alignment with research objectives.

Data Analysis Techniques

The data analysis employed both descriptive and inferential statistics to assess the model's effectiveness. The primary quantitative metric was the Normalized Gain Score (N-Gain), which measured the improvement in students' critical thinking skills by comparing pre-test and post-test results.

The normalized gain (N-Gain) was calculated using the formula:

$$(g) = \frac{Post\ test\ score - Pretest\ score}{Maximum\ score - Pretest\ score} \tag{1}$$

The N-Gain was interpreted using standard categories to indicate learning effectiveness, as shown in TABLE 1 (Amedia et. al., 2023):

TABLE 1. Interpretation of N-Gain Values

Gain Score	Categories
$0.00 \leq g < 0.30$	Low
$0.30 \leq g < 0.70$	Medium
$0.70 \leq g < 1.00$	High

In addition to measuring effectiveness, validation results from expert judgment were classified based on the average score using the Likert scale. TABLE 2 presents the standard interpretation of validation scores:

TABLE 2. Interpretation of Validation Results

Validation Results	Interpretation
$x > 4.2$	Very Good
$3.4 < x \leq 4.2$	Good
$2.6 < x \leq 3.4$	Sufficient
$1.8 < x \leq 2.6$	Poor
$x \leq 1.8$	Very Poor

An independent sample t-test was conducted to evaluate the statistical significance of the differences in learning outcomes between the experimental and control groups. Prior to this, data were subjected to normality testing using the Kolmogorov-Smirnov test and homogeneity testing using Levene's Test to ensure the validity of the t-test assumptions.

The findings from the statistical tests were used to determine whether the AI-CBL model produced significantly greater improvements in students' critical thinking skills compared to the conventional CBL approach. These analyses helped validate the instructional model and inform recommendations for broader educational adoption.

RESULTS AND DISCUSSION

Results

Characteristics of the AI-CBL Model

The AI-CBL model was developed by integrating Case-Based Learning (CBL) with an interactive Artificial Intelligence chatbot into a single, coherent instructional platform. This model is founded upon constructivist learning theory, emphasizing students' active participation in constructing knowledge through engagement with real-world cases. Simultaneously, it incorporates the principles of Technology-Enabled Learning (TEL) to ensure that the learning environment is flexible, interactive, and digitally accessible.

The instructional flow within the AI-CBL model is divided into four distinct yet interconnected phases: (1) Case Identification and Analysis, where students analyze real-world physics scenarios; (2) Case Discussion, where students explore theoretical underpinnings and discuss contextual issues; (3) Case Resolution, in which students propose evidence-based solutions; and (4) Evaluation and Reflection, where students assess the quality of their learning outcomes and reflect on their cognitive processes. Throughout all phases, the AI chatbot acts as a virtual tutor, offering prompts, scaffolding questions, and instant feedback to guide students in deeper conceptual engagement.

The model's uniqueness lies in its ability to create an authentic learning atmosphere where abstract physics theories are made tangible through contextual application. Students are encouraged to navigate complex problems with the aid of chatbot-mediated inquiry, thereby improving both their technical and reflective thinking capacities.

TABLE 3. The learning phases of the AI-CBL model in a physics learning

Learning Phase	Activities
Case Identification and Analysis	This is the initial phase of learning, where students identify and analyze various cases in which the learned theory is applied to real-life scenarios. At this stage, students select one case for further analysis. They are allowed to use the chatbot as a tool for exploration and case analysis.
Case Discussion	Individually or in groups, students discuss the case by referring to relevant theories and data. They use learning materials aligned with the analyzed case. During this process, students are encouraged to use the AI chatbot as a supporting tool
Case Resolution	Students are directed to formulate concrete solutions and recommendations for the case under study. This phase tests students' ability to apply theory to the analyzed case.
Evaluation and Reflection	Evaluation is conducted to assess conceptual understanding, analytical ability, and the quality of the proposed solutions. Additionally, students reflect on the entire learning process to identify strengths and areas for improvement

AI-CBL Learning Platform Design

To operationalize the AI-CBL model, a dedicated online learning platform was developed. The platform features essential instructional components, including digital learning materials, automated assessment instruments, and a chatbot interface integrated with a ChatGPT system. The platform supports user authentication, case assignment, interactive discussion panels, and performance analytics.

Technically, the platform was implemented as a web application with a dynamic user interface and a backend server that handles chatbot interactions using a secure API token. The platform architecture supports adaptive learning by allowing the chatbot to adjust its responses and recommendations based on each learner's previous interactions and demonstrated knowledge, thereby offering individualized learning trajectories.

FIGURE 1 illustrates the conceptual design of the AI-CBL model, which integrates Case-Based Learning (CBL) with artificial intelligence within a digital learning platform. The model consists of three main components: Technology-Enabled Learning (TEL), Constructivist Theory, and the AI-CBL learning platform itself. The platform includes E-Learning features and an AI-powered chatbot that work together to support the CBL process. TEL facilitates the development of interactive digital media, while Constructivist Theory provides the pedagogical foundation that knowledge is actively constructed by students through experience. The interaction between the E-Learning system and the AI chatbot enables students to explore case studies with guided support, thereby enhancing conceptual understanding through a student-centered approach.

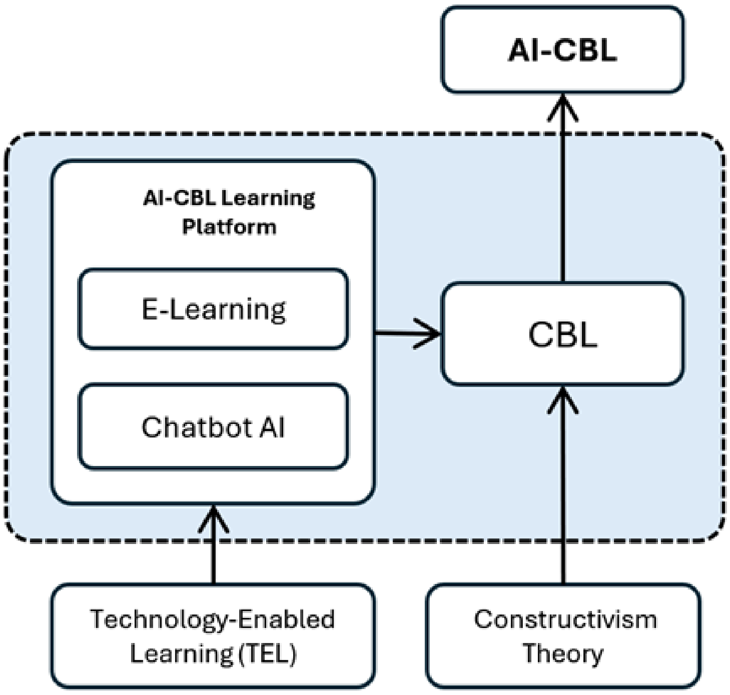


FIGURE 1. AI-CBL model design

The conceptual design in FIGURE 1 forms the core foundation of the AI-CBL system, which combines a constructivist pedagogical approach with the support of digital learning technology. The integration of E-Learning and an AI-powered chatbot within this learning platform enables the implementation of Case-Based Learning (CBL) in a more effective and structured manner. By leveraging technology and active learning principles, AI-CBL is designed to provide an adaptive, interactive, and student-centered learning experience. This model is expected to enhance students' conceptual understanding through the exploration of relevant case studies and guidance supported by artificial intelligence.

FIGURE 2 presents the conceptual design of the AI-CBL learning platform from the user interaction perspective, emphasizing the role of the student in navigating the system. At the core of the design is the Web User Interface (UI), which serves as the primary access point for students. Through this interface, students engage with the CBL stages in learning, which are guided by an integrated chatbot. The chatbot facilitates personalized interaction and supports students by delivering prompts, explanations, and assistance throughout the learning process. The system incorporates an assessment logic and feedback mechanism that evaluates student progress and provides timely responses. All user interactions, learning activities, and assessments are stored and managed in an interaction database, enabling the platform to adapt and refine the learning experience based on user behavior. This structure ensures a seamless, responsive, and user-centered learning journey.

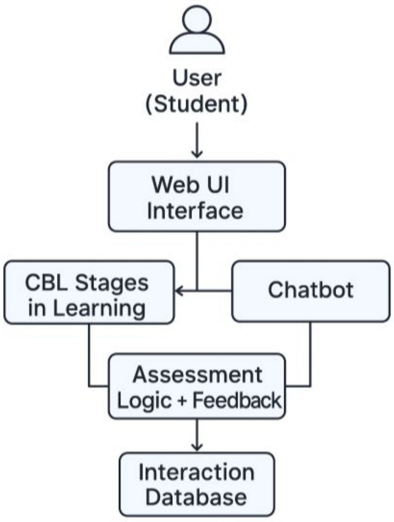
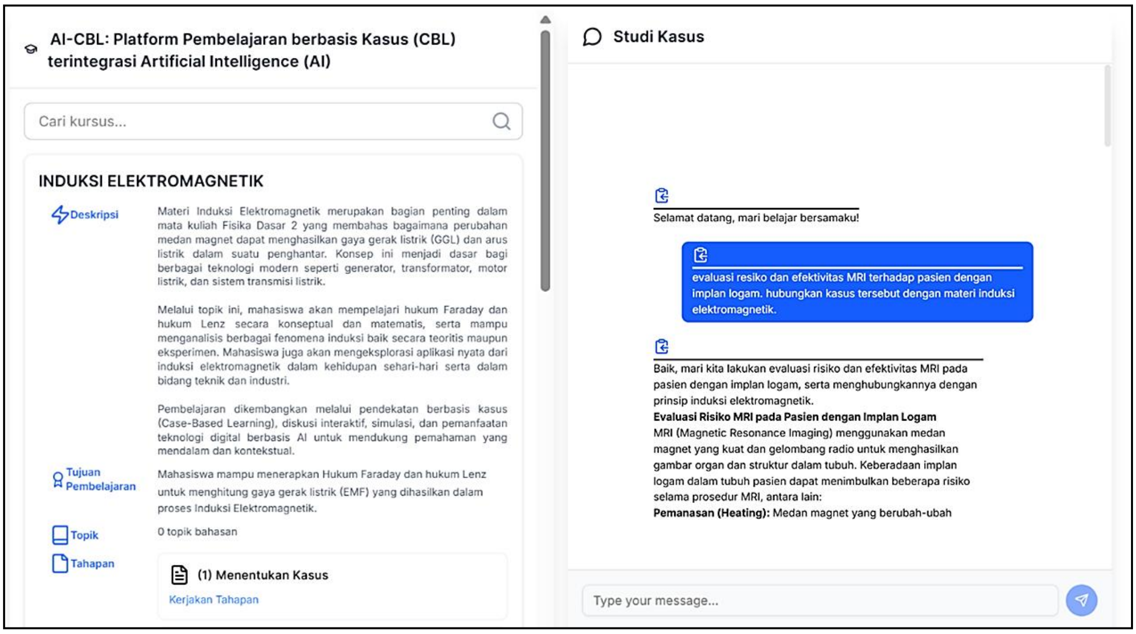


FIGURE 2. Learning Platform Development Concept Design



Materi Induksi Elektromagnetik merupakan bagian penting dalam mata kuliah Fisika Dasar 2 yang membahas bagaimana perubahan medan magnet dapat menghasilkan gaya gerak listrik (GGL) dan arus listrik dalam suatu penghantar. Konsep ini menjadi dasar bagi berbagai teknologi modern seperti generator, transformator, motor listrik, dan sistem transmisi listrik.

Melalui topik ini, mahasiswa akan mempelajari hukum Faraday dan hukum Lenz secara konseptual dan matematis, serta mampu menganalisis berbagai fenomena induksi baik secara teoritis maupun eksperimen. Mahasiswa juga akan mengeksplorasi aplikasi nyata dari induksi elektromagnetik dalam kehidupan sehari-hari serta dalam bidang teknik dan industri.

Pembelajaran dikembangkan melalui pendekatan berbasis kasus (Case-Based Learning), diskusi interaktif, simulasi, dan pemanfaatan teknologi digital berbasis AI untuk mendukung pemahaman yang mendalam dan kontekstual.

Mahasiswa mampu menerapkan Hukum Faraday dan hukum Lenz untuk menghitung gaya gerak listrik (EMF) yang dihasilkan dalam proses Induksi Elektromagnetik.

0 topik bahasan

(1) Menentukan Kasus

Selamat datang, mari belajar bersamaku!

evaluasi resiko dan efektivitas MRI terhadap pasien dengan implan logam. hubungkan kasus tersebut dengan materi induksi elektromagnetik.

Baik, mari kita lakukan evaluasi risiko dan efektivitas MRI pada pasien dengan implan logam, serta menghubungkannya dengan prinsip induksi elektromagnetik.
Evaluasi Risiko MRI pada Pasien dengan Implan Logam
MRI (Magnetic Resonance Imaging) menggunakan medan magnet yang kuat dan gelombang radio untuk menghasilkan gambar organ dan struktur dalam tubuh. Keberadaan implan logam dalam tubuh pasien dapat menimbulkan beberapa risiko selama prosedur MRI, antara lain:
Pemanasan (Heating): Medan magnet yang berubah-ubah

FIGURE 3. The AI-CBL Platform interface showing the integration of an AI chatbot within the developed e-learning system

FIGURE 3 shows the user interface of the AI-CBL learning platform, which integrates chatbot support to guide students through case-based learning. The interface provides access to course content, learning objectives, and structured stages of case study activities. In the example shown, students explore the topic of electromagnetic induction. The chatbot helps students connect theoretical concepts with real-world applications, making the learning process more interactive, user-friendly, and focused on student understanding.

Validity and Practicality Testing

The AI-CBL model underwent expert validation on media design, content relevance, and pedagogical alignment. Validation results indicated that the model met high feasibility standards in all areas. Experts gave average scores between 4.25 and 4.33 out of 5, reflecting strong agreement on the model's clarity, relevance, and instructional value.

Expert feedback highlighted the chatbot's integration as a transformative element that enhances comprehension, supports personalized learning, and enables autonomous exploration. Validators stated the AI-CBL model effectively bridges theoretical content with practical application, aligning well with modern pedagogical demands in science education.

Student feedback confirmed the model was user-friendly and engaging. More than 90% of students in the experimental group found the AI-CBL platform more interactive and stimulating than conventional instruction. Many students appreciated the chatbot's responsiveness and the immediate feedback it provided during problem-solving tasks. These insights confirm the model's viability for broader implementation in blended and digital learning.

Effectiveness of the AI-CBL Model

The primary objective of this study was to evaluate the AI-CBL model's effectiveness in improving students' critical thinking skills. To this end, students were divided into two groups: the experimental group, which utilized the AI-CBL model, and the control group, which used conventional CBL methods. Pre-test and post-test scores were analyzed for both groups. TABLE 2 presents the average test scores and the calculated N-Gain values for both groups. Building on this analysis, the following results were observed.

Specifically, the experimental group, which used the AI-CBL platform, showed a substantial increase in their post-test scores compared to their pre-test results, as shown in TABLE 4.

TABLE 4. Average pretest-posttest scores and N-gain of critical thinking skills

Group	Pretest	Posttest	N-Gain	Categories
Control Group	3.2182	3.7394	0.5212	Medium
Exp. Group	2.8649	3.8486	0.9838	High

TABLE 4 presents a comparison of the average pretest, posttest, and N-Gain scores of critical thinking skills between the control group and the experimental group. The control group, which used the conventional CBL method, achieved an N-Gain of 0.5212, categorized as medium. In contrast, the experimental group, which used the AI-CBL model, showed a much higher improvement, with an N-Gain of 0.9838, categorized as high—even though their pretest score was lower than that of the control group. These results indicate that the AI-CBL model is more effective in enhancing students' critical thinking skills. The significant difference in N-Gain scores confirms that chatbot-based interactivity within AI-CBL provides substantial added pedagogical value within the case-based learning framework.

Statistical Tests and Implementation Insights

To ensure the robustness of the findings, the data underwent several statistical analyses. The statistical test results are presented in TABLE 5. Normality was tested using the Kolmogorov-Smirnov test, and homogeneity was examined using Levene's test. Both tests yielded p-values greater than 0.05, indicating that the data met the assumptions for parametric analysis.

TABLE 5. Normality Test, Homogeneity Test, and Independent Sample T-Test

Statistical Test	Value	p-Value	Interpretation
Kolmogorov-Smirnov (Control)	0.071	> 0.05	Normal Distribution
Kolmogorov-Smirnov (Experimental)	0.200	> 0.05	Normal distribution
Levene's Test	0.203	> 0.05	Homogeneous variance
t-Test (N-Gain)	t(68) = 4.641	< 0.001	Significant difference ($p < 0.05$)

An independent samples t-test was conducted to compare the N-Gain scores between the two groups. The test yielded a t-value of 4.641 with a p-value < 0.001, indicating a statistically significant difference in learning outcomes between the experimental and control groups. These findings confirm that the use of the AI-CBL model had a strong positive impact on students' critical thinking development.

In addition to quantitative results, qualitative insights from classroom observations, interviews, and open-ended questionnaires revealed several notable strengths of the model. Students reported enhanced motivation, improved ability to apply theoretical knowledge in practical contexts, and greater autonomy in learning.

While these strengths were apparent, certain challenges emerged during implementation. These included the need for initial technical training for students unfamiliar with the platform, occasional internet connectivity issues, and variability in facilitator preparedness. Despite these obstacles, the overall reception of the model was positive, and the majority of the challenges were deemed manageable with the provision of appropriate support mechanisms.

Discussion

The findings of this study demonstrate that the AI-CBL model, which integrates Case-Based Learning with an AI-powered chatbot, significantly enhances students' critical thinking skills in physics education. This is evident from significant increases in post-test scores and high N-Gain values in the experimental group. Students also expressed positive perceptions about the learning platform's usability, interactivity, and relevance. This section outlines the primary implications of these findings and situates them within broader discussions on educational innovation, digital pedagogy, and physics instruction.

One of the most striking contributions of the AI-CBL model is its ability to serve as a pedagogical bridge between theoretical understanding and real-world application. The case-based structure allows students to engage with complex, context-driven problems that mirror actual physical phenomena, while the chatbot supports real-time exploration and iterative reflection. This combination facilitates a more profound and authentic learning experience. Such findings align with prior studies that have shown how the integration of AI into educational systems enhances students' engagement, personalizes instruction, and promotes active learning (Virkus et al., 2024; Wang et al., 2024).

The AI chatbot serves as an adaptive learning assistant, capable of responding to student queries, providing targeted prompts, and offering formative feedback throughout the case study process. This constant interactivity extends the learning process beyond classroom boundaries, supporting self-paced inquiry. In line with previous research by Cheng et al. (2024), which found that chatbots significantly enhance learner satisfaction and practical engagement, the present study confirms that AI-supported learning systems can effectively replace or complement human facilitation in digitally mediated instruction. Students using AI-CBL benefited from guided scaffolding during concept analysis and problem resolution, allowing for continuous learning loops and improved retention.

Beyond cognitive benefits, the AI-CBL model also demonstrates a measurable impact on the development of soft skills, such as communication and collaboration. These competencies are essential in scientific education, where the ability to articulate ideas and work collaboratively is crucial to scientific inquiry and problem-solving. The structured, interactive format of AI-CBL promotes peer discussion, reflective dialogue, and constructive critique, all of which foster the development of interpersonal skills. This result aligns with the conclusions of Choi et al. (2025) and Gabriella et al.

(2024), who found that AI-mediated environments enhance students' collaborative dispositions and communication effectiveness. Therefore, AI-CBL not only enhances technical proficiency but also contributes to the development of socially and cognitively competent learners.

The reflective nature of the AI-CBL process is another noteworthy aspect. Through structured engagement in the evaluation and reflection phase, students are encouraged to revisit their problem-solving strategies, assess their learning outcomes, and identify areas for improvement. These reflective activities, facilitated by both peer interaction and chatbot feedback, nurture metacognitive awareness and long-term academic growth. As highlighted by Aguilar-Mejia & Tejeda (2020), reflection is an integral component of learning that fosters deeper conceptualization and internalization of knowledge.

Despite these strengths, the implementation of the AI-CBL model presents challenges. One notable barrier identified in this study was students' initial unfamiliarity with digital learning platforms. Many required preliminary orientation and technical training to navigate the AI-CBL environment effectively. This echoes the findings of Oseremi et al. (2024), who emphasized the importance of structured digital literacy programs in supporting the integration of AI tools in education. Although the AI chatbot was well-received, it was also evident that its effectiveness was contingent upon students' prior knowledge and willingness to engage in dialogic learning. Instructors must, therefore, play an active role in scaffolding these interactions, particularly during the initial phases of adoption.

Another significant challenge lies in the digital infrastructure. Stable internet access is a prerequisite for utilizing AI-CBL effectively, and in some cases, connectivity issues hampered smooth interaction with the platform. Furthermore, the availability of well-contextualized learning resources remains limited in physics education. Most textbooks focus on abstract theories, offering little in the way of real-life case studies. This limits the effectiveness of the case-based approach and presents a challenge for educators in content development. Institutions must invest in the development of contextualized digital learning materials that align with curricular goals while being adaptable to technological platforms.

From a pedagogical perspective, the role of the instructor in AI-CBL shifts from content deliverer to learning facilitator. Teachers are required to guide students in case selection, scaffold discussions, and encourage reflective practices. This redefined role requires professional development and support to ensure that instructors can effectively mediate the AI-augmented learning process. Koehler (2022) emphasized that effective facilitation in technology-mediated environments demands pedagogical agility and digital competence, both of which must be nurtured through continuous professional learning.

While the study provides promising evidence on the efficacy of AI-CBL, further research is needed to assess its long-term impact on different learner populations and disciplines. Expanding the scope of implementation to include diverse physics topics, integrating multilingual chatbot support, and examining longitudinal learning trajectories could yield deeper insights. Additionally, investigating how chatbot algorithms can be further refined to offer adaptive assessments and personalized feedback would extend the educational value of AI systems in science learning.

In summary, the AI-CBL model offers a transformative pedagogical framework for physics education by combining the cognitive benefits of CBL with the interactivity of AI chatbot technology. It aligns with global trends toward digital and personalized learning while addressing critical pedagogical challenges in science instruction. By fostering critical thinking, promoting the development of soft skills, and offering contextualized engagement, AI-CBL responds effectively to the needs of modern learners and the demands of Education 4.0. With careful implementation and continuous refinement, this model holds significant potential for reshaping the future of STEM education in an AI-driven era.

CONCLUSION

This study concludes that the AI-CBL (Case-Based Learning with Interactive Artificial Intelligence Chatbot) model is an effective and innovative instructional approach that significantly enhances critical thinking skills in physics education. By integrating the contextual depth of CBL with the interactivity of AI chatbots, the model enables students to engage in meaningful, reflective, and autonomous learning experiences. Empirical evidence from pre- and post-test scores, N-Gain analysis, and independent t-tests shows that students in the AI-CBL group outperformed their peers in traditional CBL environments, with higher cognitive gains and increased motivation. Beyond academic achievement, the model also fosters soft skills, such as collaboration and communication, through structured, technology-enhanced interactions. Despite minor implementation challenges, such as digital literacy needs and internet accessibility, AI-CBL proves to be a replicable and adaptive learning model. Its application aligns with Education 4.0 demands, making it a recommended pedagogical innovation for future science education reforms

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