Artificial Intelligence as a Catalyst for Transforming Problem-Based Learning in Higher Education

Min Wang[1], Young Jib Yoon[1]*, Sanju Kumari Poudel[1], Hao Liu[2]

[1]Gangseo University, Gangseo District, Seoul 07661, Republic of Korea

[2]Graduate School of Woosong University, South Korea, Daejeon 34644, Republic of Korea

*Author to whom correspondence should be addressed.

Abstract

This study aims to systematically explore the theoretical underpinnings of Artificial intelligence (AI)-enabled Problem-based learning (PBL), clarify its transformative mechanisms in higher education practice, and provide theoretical and practical references for optimizing AI-integrated PBL models. To achieve this goal, the research adopts two core methodological approaches: conceptual analysis and literature synthesis.

1. Introduction

The primary findings of this study reveal three critical insights as follows:

(1) AI technologies bridge the gap between theoretical PBL frameworks and practical implementation by addressing challenges such as individualized guidance shortages and inefficient feedback loops;

(2) The integration of AI elevates the teacher's role from a traditional guide/facilitator to a "creativity catalyst" who fosters critical thinking and lifelong learning competencies;

(3) AI-enabled PBL exhibits significant potential to break disciplinary silos through collaborative, scenario-based learning tasks.

The key contributions of this research are as outlined:

(1) Establishing a clear theoretical framework that links AI technologies to constructivist and deep learning principles in PBL contexts;

(2) Synthesizing actionable practice strategies for implementing AI-PBL in higher education;

(3) Highlighting the transformative value of AI in redefining learner-teacher interactions and learning outcomes within PBL paradigms.

1.1. Research gap

Despite the growing integration of AI in higher education and the widespread adoption of PBL, existing research exhibits notable gaps. Most studies either focus on the technological affordances of AI in isolation (e.g., algorithmic improvements for learning analytics) or examine PBL pedagogy without systematically integrating

AI's potential, few investigations holistically explore how AI can be pedagogically aligned with the core principles of PBL. Furthermore, current literature rarely addresses how AI can simultaneously transform the cognitive (e.g., supporting complex problem decomposition), social (e.g., facilitating collaborative knowledge construction), and metacognitive (e.g., fostering self-regulated learning) dimensions of PBL.

1.2. Significance and research questions

To address this gap, this paper aims to:

(1) Synthesize the theoretical foundations that link AI technologies to the core principles of PBL;

(2) Identify the key mechanisms through which AI transforms PBL processes (including task design, feedback provision, and collaborative learning);

(3) Propose practical, actionable pathways for designing and implementing AI-enhanced PBL models in higher education.

To achieve these objectives, the paper addresses three core research questions:

(1) What theoretical frameworks (e.g., Constructivism, Deep Learning theory) best support the integration of AI and PBL, and how do they align to enhance learner outcomes?

(2) What specific mechanisms (e.g., adaptive task scaffolding, real-time feedback analytics) enable AI to address the limitations of traditional PBL?

(3) What practical strategies and considerations (e.g., teacher training, technology integration workflows) are essential for successfully implementing AI-enhanced PBL in higher education settings?

2. Theoretical foundation of AI-enabled PBL

2.1. The convergence of AI and PBL: From cognition to metacognition

AI connects well to PBL ideas because it can make a link between thinking and thinking about thinking. In traditional learning environments, cognitive development mainly focuses on the acquisition and application of knowledge. PBL advocates for problems that are not closed but rather complex and open-ended, stimulating students' higher-order thinking. AI tools like intelligent tutoring can give quick feedback which makes thinking stronger by helping students think about how they solve problems. Moreover, AI also stimulate students' metacognition, making students think about their own thinking so as to improve their ways and adjust their approaches according to feedback. For instance, AI-driven platforms can record student improvement, display areas needing to improve, and give suggestions on altering strategies, helping students understand their studying process better.

2.2. Educational data mining and learning analytics: Theoretical expansion of PBL

Educational data mining (EDM) and learning analytics are changing how we see and back up problem-based learning. They involve looking at big groups of numbers to find special things hiding in them that tell about teaching. Within PBL, learning analytics could track and evaluate a student's progress at any moment. It would give feedback to educators telling them how their students approach their problems and work together with classmates. AI algorithms can analyze how students behave, how they interact, what their performance is like to tell if learning would occur and which areas they had a hard time understanding. This data-driven procedure allows for finer interference, delivering person-to-person help fitting one's own learning needs.

3. Key mechanisms of AI-driven transformation of PBL

3.1. Intelligent learning analytics and personalized problem context generation

AI makes personalized learning possible with intelligent learning analytics, which keeps an eye on students' information and analyze it to create custom problems. With PBL in a traditional way, students worked on standard problems, but with AI, systems can give personalized problems based on learning progress and preferences. Student interactions with study materials and solving problems are analyzed by AI, so that the problem's difficulty and focus are adjusted according to the student's current level of knowledge and ability [1].

3.2. AI tutoring systems and virtual collaboration platforms as pedagogical support

For PBL guidance, an AI-based tutoring system is needed together with a virtual cooperation platform. AI tutors offer personal guidance by providing explanations, answering students' questions, and giving feedback that is suitable for each student. The system works as one-person tutoring and responds constantly based on students' demands. It also helps boost team spirit through virtual collaboration platforms, where students can chat with each other, share resources, and work out problems. AI can improve these platforms by recommending group dynamics based on students' strengths and weaknesses, creating team interactions that are better suited to solving certain problems. AI can also support collaboration by tracking how each group is doing and giving advice on whether different members are working well with each other [2].

4. Practical pathways for AI-enhanced problem-based learning

4.1. AI-powered natural language processing for intelligent Q&A and independent inquiry support

Natural language processing (NLP), being an AI technology, is very important for students of PBL in the process of independent inquiry. Independent Inquiry is an important part of PBL where students learn to apply their problem-solving and critical thinking skills to answer difficult questions that do not have clear right or wrong answers [3]. However, students have difficulty knowing what kind of questions to ask and finding the best sources of information. AI-driven Q&A systems, intelligent chatbots, virtual assistants, designed to give students' queries immediate answers, with contextually relevant responses fit to the exact problem in question. They understand, process, and use natural language, making interacting with the learning material feel more intuitive. Take a student working on an engineering problem, he might consult his AI assistant about certain material properties or request clarifications on technical concepts. The AI gives back fitting clarifications, urges them to extra sources, and might even propose extra regions to investigate as indicated by the student's on going inquiries [4].

Similarly, AI driven NLP systems provide more than just answers, it helps to improve the students' criticality about the material. AI analyses what type of queries are asked by the student, and after tracking the given response from the student, AI suggests some more topics of interest or extra challenges with the help of which the knowledge of the students could be improved. It makes the students to get accustomed to a habit of learning by themselves over a period of time, which is not limited to the teacher or book, rather than looking for it on their own. AI system using NLP allow the students to track their own learning progress themselves, provide quick feedback as per each individual needs, hence it aids students to think about themselves, to change their strategies to improve their metacognitive capacity.

4.2. Virtual simulation and augmented reality to enhance problem-solving experience

Simulation through virtual technology and AR with power from AI can make problem solving inside PBL environments much better [5]. These AI-driven tech give enveloping, hands-on learning experiences that imitate real-life circumstances so pupils can apply theoretical knowledge in actual scenarios. Virtual simulations give a secure, controlled setting for students to practice solving problems, do experiments, and test solutions without real-world dangers. For example, in medical class, students can learn doing surgeries or diagnosing patients on a virtual patient, so it is safe to make mistakes or to practice and they don't harm themselves. This immersive experience prompts students to take part in tackling the problem and makes learning a more lively and practical endeavor [6].

AR adds digital elements besides virtual simulation to the physical world, which makes the process of solving problems easier. AR can be used in improving PBL scenarios in order for the students to visualise and interact with the scenario in real time. For example, in an architecture course, students can use AR to see a 3D building design by moving around in a room. In this way, they could have an understanding of how abstract ideas play out in reality, so then they would be able to understand the problem better. Moreover, AR can give immediate feedback, guiding students to look at things from varying perspectives and adjusting things

immediately [7]. This interactive element makes things that were hard to learn easier to understand by giving an example that feels real.

4.3. Teacher role transformation: From knowledge transmitter to intelligent learning guide

AI in PBL means a fundamental change in the teacher's role. The traditional teacher is seen as a knowledge transmitter, imparting information to students and directing them through the structured lessons. However, in an AI-assisted PBL environment, teachers shift from teachers into facilitators /guides assisting students in navigating complex problem solving with AI taking on tasks of delivering and personalizing information to individuals. With AI covering most of the content handling, teachers can give students more room to foster critical thinking, promote collaboration, and give mentorship. AI creates information on how they do, how they act, and how they learn, so that teachers understand the experience of every student. Teachers can use it to spot students who could use some extra help, give individual advice, and step in if someone strays off course.

Additionally, AI changes the role of the teacher as a source of information into a more strategic position that helps the student to develop their thinking, solving problems, and collaboration. Teachers no longer need to spend all their time on just delivering content, as they will have time to direct students through the more complicated, interdisciplinary problems. Whereas here it is teachers acting in the roles of mentors, which is pushing students to think about their own processes, figuring things out together, coming up with ways of dealing with complicated problems [8]. At that time, the teachers can also promote metacognitive awareness among the students, thus making the students aware of their learning process and adjusting their thinking if need be. AI's continual feedback makes this possible by giving teachers a way to step in right away and give each student what they need on an individual basis, so the time it takes to learn something stays close to the things a student needs.

5. Conclusion

AI will make PBL in higher education a big change. The action of AI making use of these means not only improves the strength of PBL, but also adapts it to meet the demands of PBL in a knowledge-based society, which requires adaptability, innovation, and lifelong learning. Looking ahead to the future, as AI continues to make its way into educational ecosystems, it might open up even more chances for personal, data-based, and working learning spaces. Future research should explore cross-cultural implementations of AI-enhanced PBL and develop empirical models that validate its pedagogical impact in diverse educational contexts.

Disclosure statement

The authors declare no conflict of interest.

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