AI-Integrated Instructional Design to Enhance AI Literacy Among Pre-Service Teachers

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Abstract: The growing integration of artificial intelligence (AI) into educational tools and practices has made AI literacy an increasingly critical competency in teacher education. Pre-service teachers must be equipped to use AI both comprehensively and effectively. This study aimed (1) to explore pre-service teachers' experiences and needs related to AI in education and (2) to design and develop an AI-integrated instructional design (ID) model to enhance AI literacy. A quantitative survey was conducted using a questionnaire administered to 1,673 pre-service teachers in Thailand. A pilot test was first conducted with 30 students, and the reliability of the instrument was assessed using Cronbach's alpha. The results indicated high reliability across all items, including perceptions of AI, perceived impacts of AI, motivation to use AI, and the current learning ecosystems. No significant differences were found between STEM and non-STEM groups across these dimensions, suggesting a common need for AI training. Key training needs included (1) learning activities such as information searching, brainstorming, and discussion; (2) resources such as selected websites/blogs and online MOOC platforms; and (3) preferred instructional media, including interactive quizzes, gamified platforms, and learning management systems. Based on these findings, an ID research approach was employed to develop the AI-integrated ID framework. The initial framework was validated through an expert review by five specialists in educational technology. Grounded in design-based learning principles, the resulting framework comprises seven components: (1) Acquiring Key Contents, (2) Requirements Focus, (3) Trial Initiatives, (4) Embedding Co-Creation, (5) Manufacturing the Artifact, (6) Inspecting Results, and (7) Synthesizing Reflection. The findings provide an adaptable framework for embedding AI literacy in the teacher education curriculum and redesigning courses accordingly. The framework also highlights co-creation and design thinking as effective strategies for AI-integrated pedagogy, offering valuable insights for educators and curriculum designers seeking to enhance AI-related teaching competencies.

Keywords: Higher Education; Teacher Education; Pre-Service Teachers; AI Literacy; Instructional Design

1. Introduction

Artificial Intelligence (AI) is increasingly recognized as a transformative force in education, driving innovations such as personalized learning and data-driven assessment (Markauskaite et al., 2022). This growing influence necessitates that teachers be adequately prepared to integrate AI into their pedagogical practices. Globally, educators and policymakers have stressed that AI literacy among teachers must encompass not only technical knowledge but also the ethical, social, and cultural dimensions of AI (Ng et al., 2023). Such a comprehensive understanding enables teachers to employ AI tools to enhance student learning outcomes. Accordingly, numerous studies have emphasized the need for teacher education programs to embed AI training into curricula, thereby equipping future teachers to effectively harness AI technologies in the classroom (Sperling et al., 2024).

Pre-service teachers, as future AI-competent educators, require targeted preparation to develop AI-related competencies within educational contexts. However, many current teacher candidates remain underprepared; most lack a foundational understanding of how AI functions and, consequently, are unable to use it effectively in pedagogical settings (Du et al., 2024). Research on the integration of AI in teacher education is still emerging, yet early findings suggest that many educators experience anxiety about AI's complexity, which leads to reluctance in adopting AI tools (Du et al., 2024). In Thailand, where digital transformation is a national priority, a recent study found that teachers' AI literacy remains moderate: while many educators acknowledge AI's potential benefits, they lack the proficiency to apply AI meaningfully in practice (Chakamanont & Thabmali, 2025). This underscores a research gap in AI-focused training within Thai pre-service teacher education programs.

Addressing this need requires an instructional design (ID) approach that actively fosters AI literacy. Design-based learning (DBL) is an active learning strategy that engages learners in iterative, hands-on design processes, allowing for a deeper understanding of technological concepts (Amplo & Butler, 2023). Grounding teacher training in DBL principles may help pre-service teachers learn about AI by collaboratively designing, testing, and reflecting on AI-enhanced educational solutions. This study is also informed by the AI-TPACK framework, which

extends the established Technological Pedagogical Content Knowledge (TPACK) model to include AI-specific technological knowledge (Celik, 2023; Ning et al., 2024). The AI-TPACK framework offers a theoretical basis for identifying the competencies pre-service teachers require to integrate AI effectively into their teaching. Considering these perspectives, this study adopted a DBL approach to develop an AI-integrated instructional model for teacher education. Specifically, the research has two primary objectives: (1) to explore Thai pre-service teachers' experiences and needs regarding AI in education and (2) to design and develop a DBL-based instructional model that enhances their AI literacy.

2. Literature Review

2.1 Design-Based Learning

DBL provides pre-service teachers with authentic, problem-centered experiences that directly contribute to the development of AI literacy. In DBL environments, learners address real-world, ill-defined problems by designing AI-integrated solutions, thereby situating their learning in meaningful contexts rather than abstract theory (Gómez Puente et al., 2013). The iterative design process—comprising planning, prototyping, testing, and refining—encourages experimentation with AI-driven tools and learning through failure. This process fosters a deeper understanding of AI principles through hands-on engagement. Collaboration is another integral component of DBL. Working in teams on design challenges simulates real-world interdisciplinary work, allowing future educators to exchange knowledge and skills in AI use, ultimately enhancing their confidence and competence with the technology (Yüksel, 2025). Throughout the DBL process, structured reflection and self-assessment help pre-service teachers critically evaluate how and why they employ AI in their solutions. The key principles of DBL—authentic tasks, iterative design, collaborative learning, and reflective practice—are closely aligned with effective ID in teacher education.

DBL is rooted in constructivist, active learning strategies and is characterized by five core dimensions: (1) engagement with real-world tasks, (2) inclusion of iterative and creative problem-solving processes, (3) the teacher's role as a facilitator, (4) integrated formative assessment, and (5) a socially interactive learning context that promotes collaboration and communication (Amplo & Butler, 2023; Gómez Puente et al., 2015). In DBL settings, instructors serve as guides and scaffolds rather than content deliverers. Ongoing formative assessments, such as design reviews and reflective journals, are used to monitor progress and inform instruction. The deliberate incorporation of collaborative teamwork fosters a professional learning community in which teacher candidates actively exchange ideas and support one another's learning.

2.2 AI Literacy for Pre-Service Teachers

Teacher education frameworks are evolving to integrate AI competencies. The AI-TPACK model extends the widely adopted TPACK framework by incorporating AI-specific technological knowledge, enabling pre-service teachers to align AI tools effectively with pedagogical strategies and subject content (Celik, 2023). These models outline the knowledge and skills that teachers need to use AI meaningfully in the classroom (Bautista et al., 2024). AI technologies offer personalized, adaptive learning experiences, enhance student engagement, and support instructional tasks. Teachers proficient in generative AI tools report increased productivity and improvements in teaching strategies (Tunjera & Chigona, 2023; UNESCO, 2024). However, significant concerns persist, including issues related to ethics, bias, and academic integrity. Addressing these concerns requires educators to receive sufficient training and resources to ensure equitable and responsible use of AI technologies (Kanont et al., 2024; Zhao et al., 2022). Current research highlights the need for more focused professional development in AI, as many studies have emphasized technological capabilities over pedagogical training needs (Tan et al., 2025).

Several studies have stressed the importance of comprehensive AI literacy for pre-service teachers. This includes the ability to recognize AI technologies, understand core AI concepts, apply them pedagogically, and engage with them ethically (Long & Magerko, 2020; Ng et al., 2021; UNESCO, 2024). The empirical findings suggest that a strong conceptual grasp of AI correlates with teachers' capacity to identify educational applications of AI, implement them in classroom practice, and uphold ethical standards (Ayanwale et al., 2024). In response, teacher education programs worldwide are beginning to incorporate targeted AI literacy training. For instance, a recent professional development intervention significantly enhanced pre-service teachers' AI literacy skills, prompting calls for the integration of AI tools and activities into teacher education curricula (Younis, 2024).

3. Method

This study was conducted in two phases. In the first phase, the researchers collected data using an online questionnaire administered to 1,673 pre-service teachers through a simple random sampling method. Participants were students currently enrolled in Thai universities, and data collection took place during the fourth quarter of 2024. The pre-service teachers were categorized into two groups: (1) STEM students, who majored in science, technology, engineering, or mathematics-related fields, and (2) non-STEM students, who were studying subjects unrelated to those disciplines.

The questionnaire, developed as the primary research instrument, was pilot-tested with 30 students and comprised 38 items. These items covered various components, including student needs, experiences, and opinions about AI literacy (9 items; $\alpha = 0.878$), perceptions of AI's impact (3 items; $\alpha = 0.861$), motivation to use AI (3 items; $\alpha = 0.862$), current learning ecosystems related to AI (3 items; $\alpha = 0.787$), current AI usage (15 items), desired learning ecosystem for enhancing AI literacy (5 items), and student demographics (8 items). The results of the pilot test indicated high reliability, with all Cronbach's alpha values exceeding the acceptable threshold of 0.70. Respondents completed the questionnaire using various response types, including single-choice, multiple-select, and 7-point Likert scale formats. The data were analyzed using descriptive statistics, including frequency, mean, and standard deviation (SD).

In the second phase, the researchers analyzed key findings from the quantitative data and synthesized them with existing literature on AI literacy in education, DBL, related learning theories, and the foundations of ID. This process was used to derive the initial design principles for developing an AI-integrated Instructional Design Model (AI-IDM) aimed at enhancing AI literacy among pre-service teachers. To validate and refine the proposed design principles, five experts in the field of educational technology were purposefully selected to participate in semi-structured interviews. The experts provided feedback, offered recommendations, and validated the initial principles. The data obtained from these key informants were analyzed and used to iteratively revise and improve the AI-IDM.

4. Results

4.1 Needs and Experiences of Pre-Service Teachers

As shown in Table 1, the survey was administered to a total of 1,673 pre-service teachers. The sample comprised 570 male participants (34.07%) and 1,103 female participants (65.93%). Regarding academic year distribution, 487 respondents (29.11%) were freshmen, 654 (39.09%) were sophomores, 312 (18.65%) were juniors, and 220 (13.15%) were seniors or beyond. In terms of disciplinary background, a majority of participants were enrolled in non-STEM fields (n = 1,164; 69.58%), while 509 participants (30.42%) were from STEM-related disciplines. The average grade point average (GPAX) was 2.87 for non-STEM students and 3.20 for STEM students. Concerning digital engagement, non-STEM students reported an average of 8.86 hours of computer use per week, compared to 9.66 hours for STEM students. For internet use related to educational purposes, non-STEM students averaged 8.32 hours per week, whereas STEM students averaged slightly less, at 8.07 hours.

In the Table 1, Most participants reported having access to digital technology: 83.51% of non-STEM students and 95.68% of STEM students owned a computer with internet capability, while nearly all students owned a portable internet-enabled device (99.05% of non-STEM; 99.80% of STEM). Moreover, internet-based learning activities were widely integrated into university coursework, as reported by 99.48% of non-STEM and 99.80% of STEM students. However, institutional support for AI-related education was comparatively limited. Only 83.59% of non-STEM students and 70.14% of STEM students indicated that their faculties had provided AI training or awareness initiatives. Despite widespread access to technology, actual use of generative AI tools was significantly higher among non-STEM students (55.33%) than among STEM students (22.40%). Additionally, 21.13% of non-STEM students indicated a need for learning resources or tutors to support their use of AI tools, compared to 8.06% of STEM students. In contrast, 42.44% of STEM students reported being capable of independently learning and using AI, as opposed to 34.19% of non-STEM students.

Table 1: Participants' experiences with AI and digital tools

Questions / Items		non-STEM		STEM	
		f	%	f	%
Does your university/faculty organize teaching/training/PR on AI?	Yes	973	83.59	357	70.14
	No	191	16.41	152	29.86
Have you ever used generative AI?	Yes	644	55.33	114	22.40
	No	520	44.67	395	77.60
Do you need a learning resource or tutor to use AI?	Yes	246	21.13	41	8.06
	No	279	23.97	216	42.44
Can you learn and use AI technology on your own?	Yes	398	34.19	73	14.34
	No	241	20.70	179	35.17

Regarding the use of digital applications to support academic tasks, a majority of non-STEM students (56.27%) reported consistent use, compared to only 36.15% of STEM students. Conversely, occasional use was more prevalent among STEM students (63.65%) than their non-STEM peers (43.47%). Very few participants in either group indicated that they never used digital tools (0.26% non-STEM; 0.20% STEM). When asked about their perceived ease of using AI technologies, only 7.86% of STEM students described their experience as "effortless," whereas 18.81% of non-STEM students did. Similarly, 13.75% of STEM students and 34.45% of non-STEM students characterized AI use as "uncomplicated."

The average duration of experience with AI tools was comparable across groups: non-STEM students reported a mean of 5.20 months, while STEM students reported a slightly longer average of 5.24 months. The survey also examined the specific purposes for which AI tools were used. Common uses included creating presentations (n = 335, 7.47%), analyzing data (n = 342, 7.62%), summarizing content (n = 329, 7.33%), translating languages (n = 331, 7.38%), and brainstorming ideas (n = 298, 6.64%). Sources of awareness about AI varied. Social media was the most frequently cited channel (n = 457, 24.58%), followed by teachers (n = 423, 22.75%), friends (n = 309, 18.24%), and news websites (n = 323, 17.37%). In terms of learning pathways, most participants reported learning to use AI independently (n = 516, 37.36%), followed by peer sharing (n = 307, 22.23%) and formal training (n = 243, 17.60%).

Interest in receiving further training on AI for educational purposes was high across both experienced and inexperienced users. Among students with prior AI experience, 302 were "very interested" and 346 were "interested." Among those without prior experience, 259 expressed being "very interested," while 559 indicated they were "interested." Participants were also asked about their expectations of AI's impact on future careers. The majority in both groups anticipated a significant effect. Specifically, 277 of those with AI experience and 238 without experience believed AI would have a "great impact" on their professional futures. Additionally, a substantial number anticipated a "medium impact," especially among students without prior AI experience (n = 436), compared to 249 among experienced users.

Overall, both STEM and non-STEM students reported moderately high levels across all indicators. STEM students rated their current learning environment for supporting AI literacy slightly higher (M = 5.84, SD = 0.93) than non-STEM students (M = 5.64, SD = 1.26). Similarly, motivation to develop AI literacy was somewhat greater among STEM students (M = 5.64, SD = 0.99) than among their non-STEM peers (M = 5.49, SD = 1.22). In terms of perspectives on AI's impact, both groups again showed positive attitudes, with STEM students reporting a slightly higher mean (M = 5.69, SD = 0.95) than non-STEM students (M = 5.55, SD = 1.25). A similar trend was observed in students' self-assessments of their own AI literacy, with STEM students rating themselves higher (M = 5.78, SD = 0.83) than non-STEM students (M = 5.60, SD = 1.16).

To inform the development of effective ID for AI literacy, the study explored students' preferences regarding instructional models, learning activities, resources, and assessment tasks. A majority (65.29%) favored a blended classroom model combining face-to-face and online formats. In terms of instructional strategies, the most valued activities included peer discussion (10.40%), brainstorming (10.62%), information searching (9.20%), and self-directed learning (8.56%). As for learning resources, students preferred websites and blogs (14.61%), MOOC platforms (14.15%), video/animation content (10.71%), and e-books (13.03%). Regarding digital tools to support AI learning, students most often selected interactive quizzes (20.46%), learning management systems (LMS) (15.40%), collaborative tools like Padlet (17.37%), and gamified platforms (16.92%). The most effective

assessment formats were perceived to be educational innovation projects involving AI integration (19.14%), mini-teaching demonstrations using AI tools (18.78%), and reflective reports on AI in education (15.92%).

These findings provide a comprehensive picture of Thai pre-service teachers' engagement with, perceptions of, and aspirations toward AI literacy. While there are notable differences between STEM and non-STEM groups, both demonstrated strong interest and acknowledged AI's transformative potential in education and professional development. These insights underscore the importance of designing responsive, inclusive, and experiential learning experiences that equip future educators with practical AI competencies.

The following key findings serve as design principles for the next phase of research in Table 2:

4.2 Designing and Developing an AI-Integrated ID to Enhance AI Literacy

4.2.1 Initial Design Principles

Drawing on the findings from the previous research phases, a set of empirical design principles ([DP1]–[DP6]) was developed. To further enrich ID through digital tools and the learning environment, this study adopts Distributed Cognition (DC) as its theoretical lens. DC conceptualizes cognition as distributed across learners, tools, and the environment (Fowlin et al., 2025; Hennessy, 1993) [DP7-DP9]. Moreover, the synthesized findings from the DBL approach identified five further principles applicable to this context (Amplo & Butler, 2023; Gómez Puente et al., 2015) [DP10-DP14] in the Table 2.

Table 2: Design Principles and description for conjecture mapping

Design Principles	Details
[DP1] Flexible Learning	Blended classrooms are the most suitable formats, and ID should integrate both online and face-to-face components to support diverse learning contexts and enhance accessibility.
[DP2] Emphasize Experiential and Inquiry-Based Learning	Activities such as peer discussions, brainstorming, problem-solving, and self-directed learning were highly valued and promoted deeper understanding, critical thinking, and learning autonomy.
[DP3] Utilize Interactive and Multimedia Learning Resources	Offering AI literacy content in diverse formats promotes inclusivity and supports various learning preferences.
[DP4] Integrate Gamified and Digital Tools	Interactive quizzes, gamified platforms, and collaborative tools enhance engagement, provide real-time feedback, and support formative assessment.
[DP5] Design Tasks that Reflect Real-World Practice	Tasks such as mini-teaching demonstrations, innovation projects, and reflective reports allow students to apply their knowledge and simulate professional uses of AI in education.
[DP6] Provide Scaffolded Support and Promote Self-Regulated Learning	ID should balance autonomy with guidance through peer sharing, tutor support, and demonstration sessions with generative AI tools.
[DP7] AI as a cognitive partner	AI should be positioned as a learning support tool, such as a thinking companion that supports learners in idea generation, problem solving, and content creation. Then, the learner have to be the key decision maker and respond to validate and use the AI-genertated contents.
[DP8] Emphasizing cognitive interactions among individuals, tools, and digital environment	Learning activities should empahzie leaner to reason, analyze, and reflect while interacting with AI platforms, to enhance the distributed cognition across human and digital learning ecosystem.
[DP9] Knowledge co-creation through social interaction and collaborative learning activities	Learners should be encouraged to co-construct knowledge through peer collaboration or Think-Pair-Share activities.
[DP10] Engagement with real-world tasks	Students should apply AI tools to solve practical problems or conduct educational tasks based on current classroom challenges.
[DP11] Iterative learning design	Learners should experiment with AI tools in multiple rounds, improving their outputs based on AI feedback, peer input, or instructor guidance
[DP12] Collaborative learning	Collaboration should be embedded through group discussions, co-design tasks, and interactive challenges that require collective reasoning and shared responsibilities among peers.
[DP13] Reflective practice	Learners should do the reflection on their experiences using AI, examining how their understanding, what ethical considerations, and how AI biased their cognitive.

Design Principles	Details
[DP14] Facilitator support	Instructors are a key man in scaffolding AI literacy by presenting responsible AI use, unitize appropriate AI tools, and providing just-in-time feedback.

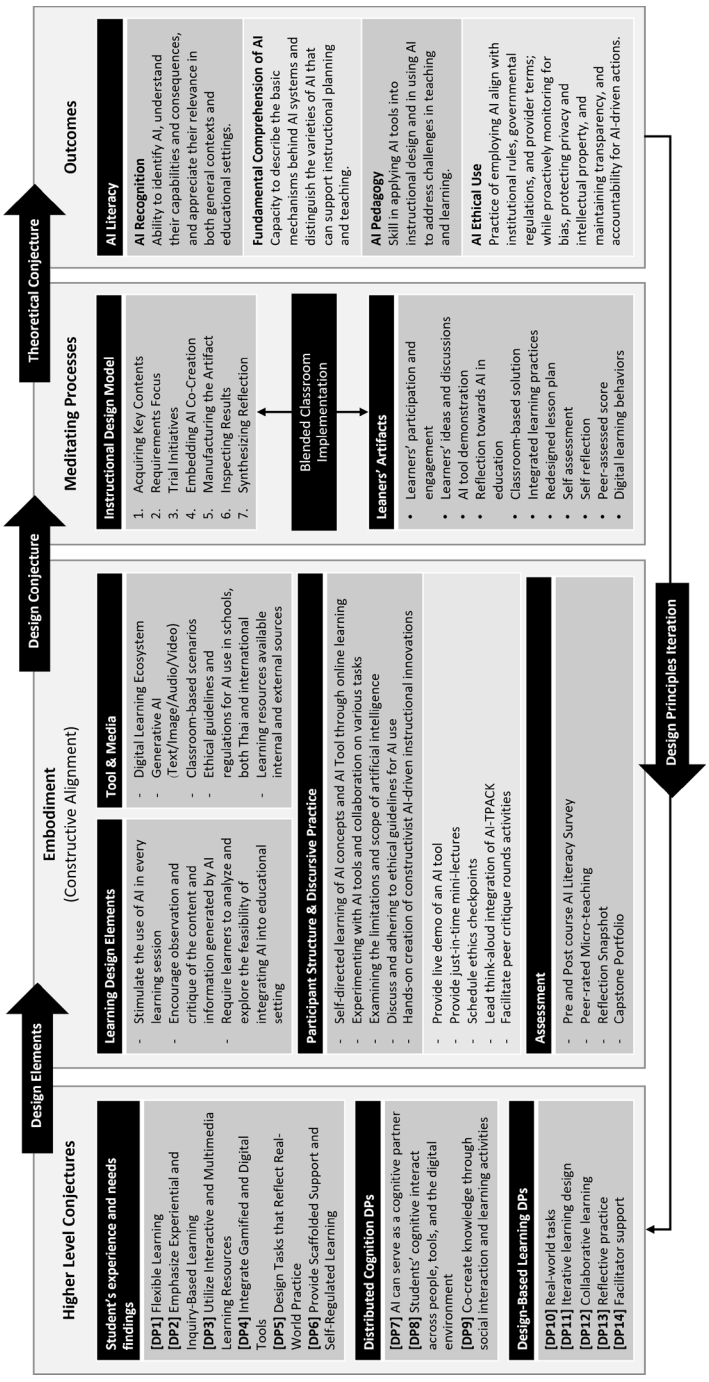

Figure 1: Initial conjecture map of AI-integrated ID to enhance AI literacy

To structure the AI-integrated ID, these 14 design principles were mapped using Sandoval's (2014) conjecture mapping approach. This method explicitly links theory, design embodiments, mediating processes, and expected learning outcomes. In the conjecture map, "higher-level conjectures" are derived from learner needs and theories of DC and DBL. The design embodiment includes AI-integrated learning activities, tools, and media; collaborative and self-directed learning structures; ethical discussions; and practical applications of AI tools. These processes generate mediating processes such as co-creation, critical reflection, and knowledge application, which lead to measurable outcomes in literacy development, as shown in the following **Figure 1**.

As a result, the proposed framework—designed as a classroom-oriented ID model—comprises the following seven key components as the **Figure 2**:

- [1] Acquiring Key Contents: Provides foundational knowledge of AI concepts and integration frameworks (e.g., AI-TPACK) through demonstrations and guided study, thereby establishing a solid conceptual base.
- [2] Requirements Focus: Defines the educational design challenge as a practical, real-world problem, ensuring that AI applications are aligned with specific pedagogical objectives.
- [3] Trial initiatives: Learners generate preliminary ideas and develop prototype solutions, promoting hands-on exploration of AI tools.
- [4] Embedding AI Co-Creation: Involves the collaborative refinement of these solutions with AI systems, peers, and instructors, integrating AI meaningfully into the creative process.
- [5] Manufacturing the Artifact: Learners construct tangible outcomes such as functional AI prototypes or AI-enhanced lesson plans, translating abstract ideas into applied practice.
- [6] Inspecting Results: Entails evaluating the effectiveness of the solutions and engaging in peer feedback and reflection.
- [7] Synthesizing Reflection: Encourages learners to articulate insights, synthesize lessons learned, and identify best practices to guide further iterations.

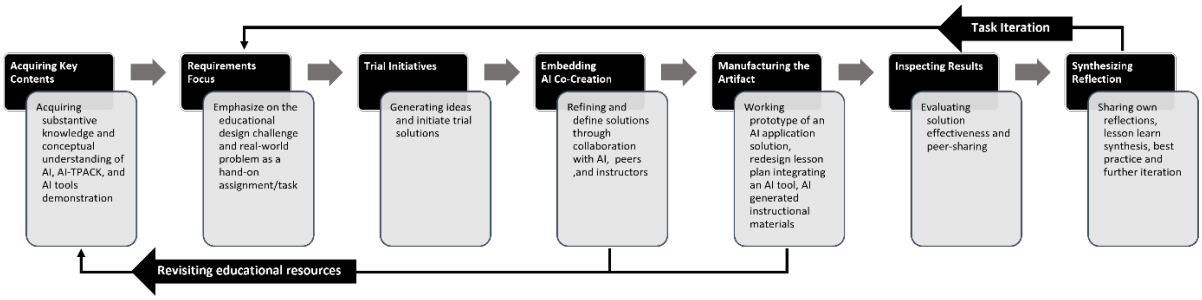

Figure 2: Proposed framework of AI-integrated ID model

Based on expert suggestions from interviews, the overall design principles and the ID model were considered applicable to real-world educational contexts. Accordingly, the author revised and refined the design principles to further develop the conjecture map, as shown in the **Table 3** below.

Table 3: Experts' suggestions and revisions to the design principles for AI-Integrated ID Model

Initial Design Principles	Experts' Suggestions	Iterated Design Principles
Student's Experience and Needs Findings [DP1−6]	• Provide additional declarative and procedural knowledge about AI tools as just-in-time learning resources, such as prompting skills, TPACK case studies, and ethical issues in education • Emphasize more non-AI learning activities to increase AI awareness and reduce cognitive offloading • Be aware of AI overuse during self-paced or online learning • Facilitate student discussions and group reflection on AI in education to promote AI literacy	**Added:** [DP15] Self-paced learning modules via multimedia **Modified:** [DP8] Students' cognitive interaction across people, tools, and the digital environment via classroom guidelines [DP9] Co-creating knowledge through social interaction, AI, and learning activities [DP12] Collaborative ideating with peers [DP13] Reflective practice for individuals and groups
Distributed Cognition DPs [DP7−9]		
Design-Based Learning DPs [DP10−14]		

Hence, the proposed AI-Integrated Instructional Design (ID) Model has not yet been implemented to evaluate its effectiveness among pre-service teachers. To address this, the author plans to develop a digital learning ecosystem to serve as a mediating platform for the model's deployment in the upcoming academic semester. The implementation will take place in a blended learning environment, embedding the model's phases into weekly learning activities for a cohort of pre-service teachers enrolled in an educational technology course. Both formative and summative evaluations will be conducted through pre- and post- self-assessments of AI literacy, classroom observations, and learner reflections. During the implementation, the reseachers acknowledge ethical implications of AI in teacher training, including concerns of bias, privacy, and algorithmic transparency,

and commit to critically evaluating these aspects in the model's future development and implementation. Then, this phased implementation approach will support iterative refinement of the instructional model and its underlying design principles based on real-world classroom feedback, thereby enhancing both its practical practice and theoretical conception.

5. Discussion

Pre-service teacher education programs should be reimagined to embed AI literacy throughout the curriculum or related courses. This approach aligns with international recommendations that digital and AI competencies should be mainstreamed in initial teacher training, ensuring that all future educators can confidently and ethically employ AI tools (OECD, 2023). Similarly, UNESCO's *AI Competency Framework for Teachers* urges teacher education systems to cultivate the knowledge, skills, and values necessary for ethical and effective AI integration in classrooms (UNESCO, 2024).

The proposed model includes the integration of AI fundamentals into teachers' reflective practices. This aligns with the findings of Ayanwale et al. (2024), who reported that increased AI knowledge predicted improvements in AI use, detection, ethics, creation, and problem-solving. In addition, insights from the model underscore the importance of embedding AI in various subject areas and learning activities. Effective instructional strategies emphasize hands-on AI applications paired with collaborative discussions which grounded with social-constructivist through peers interaction and the help of others for co-creating knowledge and shared experiences and perspectives. Ding et al. (2024) found that a case-based professional development sequence—beginning with an introductory AI lecture and progressing to complex case scenarios—significantly enhanced teachers' AI-related problem-solving abilities.

The ID of AI literacy initiatives should integrate a theoretical learning environment with practical application and ethical inquiry. Tammets and Ley (2023) proposed a teacher-centered model in which curriculum development is intertwined with AI tool co-creation. In this model, teachers' "professional vision" informs the design of AI solutions, fostering deeper pedagogical reasoning. In the context of the current study, this may involve pre-service teachers engaging in the *Embedding AI Co-Creation* stage by designing an AI-powered educational artifact, followed by the *Inspecting Results* stage, where they analyze AI-generated data or feedback to refine instruction. The final stage, *Synthesizing Reflection*, encourages a critical evaluation of AI's influence on learning and teaching decisions, situating AI literacy within broader pedagogical objectives.

This study has several limitations. First, it was conducted over a short period, limiting participants' ability to observe longitudinal changes in AI literacy or assess sustained pedagogical impact. Second, as the proposed AI-IDM has not yet been implemented in actual classroom settings, its effectiveness is inferred only from expert judgments rather than empirical evidence. Third, all data were obtained from Thai pre-service teachers, thus restricting the generalizability of the findings to other cultural, technological, and curricular contexts.

Although this study introduces a theoretically grounded AI-IDM, it remains a proposed framework. A systematic implementation phase is essential for evaluating the pedagogical efficacy of the model and refining its components. Specifically, a quasi-experimental design that integrates learner performance data with qualitative evidence would enable the triangulation of results. Moreover, while the model's design principles are currently anchored in DBL and DC, they can be enriched through the integration of complementary theoretical perspectives. For instance, socio-constructivist frameworks may support the collaborative nature of AI co-creation, while self-determination theory and digital critical thinking models could inform learner motivation and higher-order reasoning.

Ethics Declaration

This paper ethical permission was obtained from Chulalongkorn University (reference number 429/67). Therefore, all research participants' identities and data remain unidentifiable and will be deleted immediately after the research is completed. All participants consented to the data for research purposes.

AI Declaration

The authors declare that they have used AI tool, Grammarly to proofreading and enhance the readability of this manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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