Journal of Education and Learning (EduLearn)
Vol. 20, No. 4, November 2026, pp. 2594~2602
ISSN: 2089-9823, DOI: 10.11591/edulearn.v20i4.26984

Developing an AI-integrated mathematics learning model to enhance digital literacy: evidence from bilingual and non-bilingual contexts

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Article Info

Article history:

Received Dec 10, 2025
Revised Feb 25, 2026
Accepted Jun 6, 2026

Keywords:

Artificial intelligence
Bilingual education
Digital literacy
Mathematics learning model
Plomp model

ABSTRACT

This study addresses the pedagogical gap between artificial intelligence (AI) integration and digital literacy development by developing and validating the artificial intelligence–integrated mathematics learning model (PMAI-e). Employing the Plomp research and development (R&D) framework, the study produced a comprehensive instructional model validated by experts with a high validity score (Avg. 3.64) and confirmed as practical by users. To evaluate effectiveness, a quasi-experimental study was conducted with 163 undergraduate mathematics students selected via cluster random sampling. Participants were divided into three groups: experimental group 1 (bilingual), experimental group 2 (non-bilingual), and a control group using conventional project-based learning. Data were analyzed using N-Gain, analysis of variance (ANOVA), and Tukey honestly significant difference (HSD) post-hoc tests. The results demonstrated that the PMAI-e model significantly enhanced digital literacy skills compared to the control group (p<0.001). The bilingual group achieved the highest improvement (N-Gain=0.71), followed by the non-bilingual group (N-Gain=0.67), with both significantly outperforming the control group (N-Gain=0.34). Notably, the two experimental groups differed significantly, according to post-hoc analysis (p=0.012), suggesting that integrating bilingual instruction with AI-supported pedagogy offers additive benefits to digital literacy development. The PMAI-e model is recommended as a scalable framework for fostering ethical and technical AI competencies in higher education.

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1. INTRODUCTION

The quick development of artificial intelligence or AI in higher education has presented new chances for personalized learning, adaptive feedback, and data-driven instructional decision-making. Prior research indicates that AI may improve automate routine assessment processes, student engagement, and facilitate individualized learning pathways across various disciplines [1]–[5]. However, studies also highlight ongoing challenges related to technological readiness, privacy concerns, and uneven institutional adoption, suggesting that AI integration requires thoughtful pedagogical design to ensure meaningful learning outcomes [6]–[9]. Recent analyses from previous studies emphasize risks such as overreliance on AI tools, diminished metacognitive engagement, and the need to cultivate ethical awareness when using AI in academic settings [10], [11]. These results underline the significance of developing structured models that balance technological innovation with critical, autonomous, and responsible learning practices.

Digital literacy, at the same time, has become a necessary competency for students navigating AI-rich learning environments. Studies in Indonesian higher education report substantial variation in students' abilities to evaluate communicate responsibly online, digital information, and use digital tools effectively for academic purposes [12]–[14]. Digital literacy, according to broader international literature, is a multifaceted notion that includes technological competence, cognitive and evaluative abilities, social-emotional communication, and ethical awareness [15]–[17]. Despite increasing recognition of this complexity, insights from previous studies reveal inconsistencies in how digital literacy is embedded in mathematics curricula and highlight the limited availability of validated assessment tools designed specifically for AI-supported learning contexts [18], [19]. These findings indicate the need for instructional designs that position digital literacy as an integral component of mathematics learning, particularly as students interact with AI tools.

Although an expanding body of studies demonstrates the advantages of AI in mathematics learning, such as AI-assisted tutoring systems that provide personalized support or adaptive platforms that improve performance and self-directed learning [20]–[22], many studies focus primarily on improving content mastery rather than on cultivating broader digital literacy competencies. Prior study findings reinforce that existing models rarely address the ethical, metacognitive, and autonomy-related dimensions of AI use in mathematics learning, leaving gaps in students' preparedness to use AI tools critically and responsibly [23], [24]. Research in mathematics education also shows that instructional practices often remain conventional, with limited incorporation of AI tools or opportunities for students to develop digital literacy within mathematical problem-solving and project-based activities [10], [25], [26]. Collectively, these findings suggest that although AI and digital literacy are increasingly recognized as essential for modern mathematics education, current approaches tend to treat them separately and lack comprehensive frameworks that explicitly integrate both domains.

Given these conditions, the central problem addressed in this study concerns the absence of structured pedagogical models that guide the AI integration tools into mathematics learning while simultaneously supporting the development of students' multidimensional digital literacy skills. Previous studies point to gaps in existing models, particularly the lack of instructional frameworks that incorporate responsible and ethical AI use, critical thinking, and sociocultural contextualization alongside mathematics content [27]–[30]. These insights highlight the need for instructional innovations that unify AI integration, information and communication technology (ICT) use, and digital literacy development within coherent learning environments.

In response to these gaps, this study introduces the artificial intelligence-integrated mathematics learning model (PMAI-e), designed to integrate AI tools, ICT, and project-based learning with sociocultural interaction patterns rooted in the Bugis-Makassar context. The model is distinguished by its emphasis on digital literacy as an explicit learning outcome, its attention to ethical and responsible AI use, and its comprehensive suite of instructional materials developed and validated through expert review, practicality testing, and empirical implementation. By addressing the persistent fragmentation between AI-supported instruction and digital literacy development, the PMAI-e model offers a structured pedagogical approach that aligns with emerging demands in higher education mathematics learning. Accordingly, the purpose of this study is to develop, validate, and evaluate the PMAI-e model using the Plomp development framework and to examine its potential to enhance university students' digital literacy skills.

2. METHOD

2.1. Research design

The PMAI-e was developed, validated, and experimentally evaluated in this study using a research and development (R&D) methodology. The study was conducted in higher education settings in South Sulawesi, Indonesia, with the overarching goal of enhancing university students' digital literacy skills through purposeful AI integration and ICT within mathematics learning. The Plomp development model [31] was adopted as the methodological framework, comprising five interrelated phases—preliminary investigation, design, realization/construction, test–evaluation–revision, and implementation. This structure ensured that the model was theoretically grounded, systematically refined, and empirically tested before full-scale application.

2.2. Development procedures

The research procedure began with the preliminary investigation phase, which included field observations, needs analysis, and assessment of baseline digital literacy levels. Findings from this phase identified significant gaps in the AI tools integration in mathematics instruction and inconsistent emphasis on ethical, evaluative, and cognitive aspects of digital literacy. These insights informed the design phase, during which the PMAI-e model was conceptualized by synthesizing constructivist learning theory with Bugis-Makassar sociocultural interaction patterns. The model's syntax was structured into five sequential learning phases, ensuring alignment between AI-assisted learning activities and the advancement of students' 21st-century skills.

In the realization phase, the conceptual design was transformed into prototype-1, consisting of a comprehensive suite of instructional materials: the model book, lecturer handbook, student handbook, student worksheets (LKM), and semester learning plans (RPS). These products operationalized the theoretical underpinnings and instructional flow defined in the design phase. Prototype-1 then underwent expert validation and iterative refinement, producing prototype-2 (validated model) and later prototype-3 (practical model) following limited classroom trials.

2.3. Experimental design

A quasi-experimental study design with a non-equivalent control group design was used to evaluate the PMAI-e model's effectiveness. Three groups were compared: i) experimental group 1 (bilingual program); ii) experimental group 2 (non-bilingual program); and iii) a control group implementing conventional project-based learning without structured AI integration. Participants were undergraduate mathematics students from both public and private universities selected using cluster random sampling. The total sample comprised 163 students distributed across three classes: experimental group 1 (n=67), experimental group 2 (n=63), and the control group (n=33). This distribution reflects the natural class sizes of the participating institutions.

In this study, bilingual instruction refers to the systematic utilization of Indonesian and English as instructional languages. Bilingual implementation was consistently applied across learning instructions, AI prompts, project documentation, and student presentations. Both experimental groups adhered to identical instructional designs, learning objectives, assessment criteria, and AI tools; differences between the bilingual and non-bilingual conditions were limited to linguistic scaffolding. This design ensured that any observed differences in learning outcomes could be attributed to language-mediated instructional processes rather than variations in content or technology use.

2.4. Instruments and data collection

To assess the model's validity, practicality, and effectiveness, multiple instruments were employed. Expert validation sheets evaluated the theoretical foundations, syntax coherence, linguistic clarity, social system, reaction principles, and support structures. Practicality was measured using observation checklists and lecturer-student response questionnaires during limited implementation. A pre-test and a post-test were used to obtain effectiveness data. The test items were operationalized based on three key dimensions of digital literacy: i) information processing (locating and evaluating digital resources); ii) content creation (utilizing AI tools to generate mathematical solutions); and iii) ethical awareness (citation and responsible AI use). The instrument underwent empirical validation and reliability testing; the estimated reliability using Cronbach's alpha was 0.804, indicating the instrument's reliability for data collection.

Digital literacy was conceptualized as a multidimensional construct encompassing information processing, content creation using AI tools, and ethical awareness. The assessment instrument was designed to capture these dimensions through integrated task-based items. For evaluating overall model effectiveness within the experimental design, data analysis employed a validated composite score representing students' overall digital literacy performance. While this approach supports model-level evaluation, future research may disaggregate dimension-level outcomes to provide more fine-grained insights into specific areas of digital literacy development.

2.5. Data analysis

The validity and practicality analyses were conducted descriptively by calculating mean scores from expert reviews and classroom observations. To determine the effectiveness of the PMAI-e model, normalized gain (N-Gain) scores were computed to quantify improvement in digital literacy across the three groups [32]. Significant differences in digital literacy outcomes were examined using inferential statistics and one-way analysis of variance (ANOVA) [33]. Normality and homogeneity tests were administered as prerequisite analyses to ensure that ANOVA assumptions were met. To determine whether there is a significant difference in the N-Gain scores of digital literacies between experimental group 1 (bilingual), experimental group 2 (non-bilingual), and the control group, the hypotheses were developed to direct inferential analysis.

2.6. Implementation of the PMAI-e model

The implementation phase followed the five-phase syntax of the PMAI-e model: i) perception and objectives, introducing AI concepts and situating learning within cultural context; ii) representation, where students collaboratively developed project plans grounded in community interaction principles; iii) AI assistance, involving supervised use of AI tools for project development while ensuring academic integrity and critical engagement; iv) review and monitoring, during which lecturers evaluated AI-assisted outputs and facilitated concept abstraction; and v) plenary and evaluation, where students presented and debated findings to refine mathematical and digital literacy understanding.

2.7. Structure and instructional flow of the PMAI-e model

The PMAI-e model is supported by a structured instructional module consisting of a model book, lecturer handbook, student handbook, semester learning plans, student worksheets, and project-based assignments. These materials are designed to ensure coherent implementation of AI-assisted mathematics learning while explicitly fostering digital literacy as a core learning outcome.

Instructional activities are organized into five sequential phases that guide students from orientation to reflection. The first phase, perception and objectives, introduces learning goals, expectations for digital literacy development, and principles of ethical and responsible AI use, thereby establishing conceptual readiness. The second phase, representation, engages students in collaborative project planning through guided resources, structured prompts, and negotiated problem representations.

The third phase, AI assistance, involves supervised use of AI tools to support information processing and content creation. At this stage, students are required to critically evaluate AI-generated outputs, reformulate solutions using their own academic language, and acknowledge AI assistance appropriately. The fourth phase, review and monitoring, emphasizes lecturer-guided feedback, peer discussion, and conceptual abstraction to consolidate mathematical understanding and prevent overreliance on AI tools.

The final phase, plenary and evaluation, consists of project presentations, formative quizzes, and reflective discussions aimed at synthesizing mathematical concepts and digital literacy skills. Formative assessments embedded throughout the module serve diagnostic, reflective, and evaluative purposes, enabling lecturers to monitor learning progress while supporting usability, instructional clarity, and navigability across learning activities.

3. RESULTS AND DISCUSSION

The findings of this study are displayed in two main parts: the development of the PMAI-e model (R&D outcomes) and the empirical testing of its effectiveness (experimental outcomes).

3.1. The model development

3.1.1. Preliminary investigation and design results

The initial investigation identified the absence of structured pedagogical frameworks that systematically integrate artificial intelligence into mathematics learning while simultaneously fostering digital literacy. Observations and needs analysis showed limited use of AI-assisted tools in existing instructional practices and insufficient emphasis on ethical and evaluative aspects of digital literacy. These results showed the design of the PMAI-e model, which incorporates constructivist learning principles and sociocultural interaction patterns rooted in Bugis-Makassar values. The model syntax was structured into sequential phases intended to facilitate AI-supported project-based learning.

3.1.2. Product realization (prototype-1)

During the realization stage, the conceptual design was transformed into a complete instructional package referred to as prototype-1. This prototype included the PMAI-e model book, lecturer and student handbooks, LKM, RPS, project assignment guides, and digital literacy assessment instruments. Each component was developed to reflect the theoretical underpinnings and instructional flow defined in the design phase.

3.2. The validation (prototype-2)

To evaluate the validity of prototype-1, expert validators conducted assessments across components such as theoretical foundations, model syntax, language, reaction principles, social system, instructional impacts, support system, and implementation feasibility. Table 1 summarizes the validation outcomes. The overall average validity score was 3.64, which falls into the highly valid category, as Table 1 illustrates. The learning model syntax component received the highest rating (3.80), indicating that the phases of AI integration and project-based learning were logically sequenced and well-defined. Based on these results, the model was declared to meet the validity criteria and was revised into prototype-2.

Table 1. Summary of expert validation results for the PMAI-e model

Component	Average score	Category
Development foundation	3.51	Highly valid
Language	3.57	Highly valid
Learning model syntax	3.80	Highly valid
Social system	3.55	Highly valid
Reaction principle	3.73	Highly valid
Support system	3.60	Highly valid
Instructional and companion impact	3.65	Highly valid
Implementation of learning model	3.70	Highly valid
Total average	3.64	Highly valid

3.3. The practicality (prototype-3)

Prototype-2 underwent limited implementation to evaluate its practicality and usability in actual classroom settings. Observations revealed that the model's instructional phases were executed as intended with a high degree of fidelity. Analysis of the practicality questionnaires yielded an average lecturer response score of 3.49 (practical) and an average student response score of 3.54 (practical). These scores suggest that the supporting documents were user-friendly and the integration of AI tools was transparent to the users. The alignment between planned syntax and actual execution resulted in prototype-3. Although AI-supported learning activities generated interaction data during the implementation of the PMAI-e model, system-level AI interaction logs (such as time-on-task or frequency of hint usage) were not included in the present analysis. The study's focus was on pedagogical effectiveness and learning outcomes rather than learning analytics. User experience indicators—including usability, cognitive load management, and navigability—were indirectly evaluated through lecturer observation sheets and student practicality questionnaires. The results indicated that the phased instructional structure and continuous lecturer scaffolding supported a clear, manageable, and user-friendly learning experience.

3.4. The effectiveness (experimental study)

Using pre-test and post-test data from three groups, the PMAI-e model's efficacy in improving students' digital literacy abilities was investigated. One-way analysis of variance (ANOVA) was used to examine the variations in the improvement of digital literacy; the findings are shown in Table 2. The study reveals statistically significant disparities across the groups, suggesting that the impact of the intervention on student results was uneven.

Table 2. Results of ANOVA for differences in digital literacy scores

Variation source	Sum of squares	df	Mean square	F	Sig.
Between groups	3.244	2	1.622	222.063	0.000
Within groups	1.143	160	0.007		
Total	4.387	162			

The mean pre-test and post-test scores, as well as the N-Gain score for each group, are shown in Table 3. While all groups exhibited improvement, both experimental groups demonstrated significantly higher gains compared to the control group. Notably, the bilingual group achieved the highest post-test mean and N-Gain score. The N-Gain scores employed to quantify the extent of enhancement across groups reveal distinct learning gains. With the highest N-Gain score of 0.71, experimental group 1 (bilingual) was categorized as high. With an N-Gain of 0.67, experimental group 2 (non-bilingual) was classified as medium. conversely, the control group demonstrated substantially lower improvement with an N-Gain score of 0.34.

Table 3. N-Gain scores for digital literacy improvement

Group	Pretest mean	Post-test mean	N-Gain score	Category
Experimental group 1 (bilingual)	46.37	84.06	0.71	High
Experimental group 2 (non-bilingual)	41.03	80.19	0.67	Medium
Control group	33.12	55.58	0.34	Medium

The ANOVA results confirm that the differences among the three groups are statistically significant ($F=222.063$, $p<0.001$). To determine which groups exhibited statistically significant differences, a Tukey HSD post hoc analysis was conducted on the N-Gain scores. The outcomes are presented in Table 4.

Table 4. Summary of post-hoc test results (Tukey HSD) on digital literacy N-Gain

Group (I) vs. Group (J)	Mean difference	Std. error	Sig.
Experimental group 1 (bilingual)-control	0.37*	0.018	0.000
Experimental group 2 (non-bilingual)-control	0.33*	0.018	0.000
Experimental group 1 (bilingual)-experimental group 2 (non-bilingual)	0.04*	0.015	0.012

Note: *the mean difference is significant at the 0.05 level.

The post-hoc analysis confirms that both experimental groups utilizing the PMAI-e model significantly outperformed the control group ($p<0.05$). Furthermore, the comparison between the two experimental variations reveals a statistically significant difference ($p=0.012$); specifically, the bilingual group (experimental group 1) achieved a higher mean gain (0.04 higher) than the non-bilingual group (experimental group 2). These findings suggest that while the PMAI-e model is highly effective regardless of language setting, the integration of bilingual instruction may offer a slight but significant additive benefit to digital literacy development.

3.5. Discussion

The findings indicate that the PMAI-e model represents a valid, practical, and effective pedagogical framework in integrating artificial intelligence into mathematics instruction with a clear emphasis on developing digital literacy. The significant differences identified between the control and experimental groups suggest that structured AI integration, when guided by sound pedagogical principles, can improve students' capacity to process information, produce content responsibly, and interact ethically with digital technologies [1], [6], [9], [11].

The superior performance of both experimental groups aligns with previous research emphasizing that AI-supported learning environments yield positive outcomes when combined with instructional scaffolding and reflective activities rather than unregulated tool usage [1], [22]. Unlike approaches that treat AI merely as a performance-enhancing technology, the PMAI-e model positions AI as a cognitive support system embedded within project-based learning. This design directly addresses concerns raised in earlier studies regarding overreliance on AI and diminished metacognitive engagement by ensuring continuous lecturer supervision and structured reflection phases [34], [35].

A notable contribution of this study is the significant difference observed between the bilingual and non-bilingual experimental groups. The higher N-Gain achieved by students in the bilingual condition suggests that linguistic scaffolding using Indonesian and English may have fostered deeper cognitive processing and academic communication. Engaging with mathematical concepts and AI-generated information across two languages likely required students to reformulate ideas, evaluate meaning more critically, and articulate reasoning with greater precision. This finding is consistent with theoretical perspectives that view bilingual instruction as a catalyst for metacognitive awareness and higher-order thinking, particularly in technology-enhanced learning contexts [6], [36]–[38].

It is important to interpret these findings in light of the study's methodological scope. Digital literacy was analyzed using a validated composite score to assess overall model effectiveness rather than dimension-level outcomes. While this approach supports evaluation at the pedagogical model level, it limits conclusions regarding the relative contribution of specific digital literacy domains. Additionally, although AI-supported learning activities generated interaction data during implementation, system-level AI interaction logs were not included in the analysis. Future research may integrate learning analytics to examine how patterns of AI interaction relate to student engagement and learning trajectories [39].

Despite these limitations, the PMAI-e model offers a scalable and context-sensitive solution for higher education mathematics instruction. By embedding ethical AI use, linguistic scaffolding, and socioculturally grounded collaboration within a coherent instructional structure, the model transforms AI from a potential shortcut into a medium for critical inquiry. These findings extend existing literature by demonstrating how pedagogically guided AI integration can simultaneously support disciplinary learning and multidimensional digital literacy development [4], [27], [40].

4. CONCLUSION

This study designed, validated, and assessed the PMAI-e as a structured pedagogical framework aimed at strengthening university students' digital literacy skills. Using the Plomp development model, the study produced a comprehensive instructional system that was confirmed to be highly valid and practical for classroom implementation. The experimental results provide robust empirical evidence of the model's effectiveness. The PMAI-e model significantly improved students' digital literacy compared to conventional project-based learning. Specifically, the bilingual experimental group achieved the highest improvement, followed by the non-bilingual experimental group, both of which were significantly higher than the control group. A critical finding from the post-hoc analysis is the statistically significant difference between the two experimental groups, indicating that implementing the PMAI-e model within a bilingual instructional context yields an additive benefit to digital literacy development. This suggests that the cognitive demands of navigating dual languages, when paired with structured AI interaction, may foster deeper evaluative and metacognitive engagement. By addressing the gap between AI integration and competency development, the PMAI-e model offers a scalable solution for higher education. It transforms AI from a potential shortcut into a tool for critical inquiry. Future research should explore the longitudinal impact of this model across other science, technology, engineering, and mathematics or STEM disciplines to determine if the bilingual advantage persists in different subject areas.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Ministry of Higher Education, Science, and Technology of Indonesia, Universitas Negeri Makassar’s Research and Community Service Institute (LP2M) and the Directorate General of Higher Education, Research, and Technology for their support, guidance, ongoing assistance and direction during the project. Additionally, gratitude is expressed to all the people and organizations whose assistance made this study possible.

FUNDING INFORMATION

The Republic of Indonesia’s Ministry of Higher Education, Science, and Technology provided funding for this study through a Fundamental Research Grant with the number 084/C3/DT.05.00/PL/2025.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
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So : **So**ftware
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I : **I**nvestigation
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D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest related to this study.

INFORMED CONSENT

All participants in this study have provided their informed consent.

ETHICAL APPROVAL

The study involving human participants was conducted in compliance with all relevant national regulations and institutional policies. It adhered to the ethical principles outlined in the Helsinki Declaration and obtained approval from the authors’ institutional review board or an equivalent ethics committee.

DATA AVAILABILITY

The data supporting the conclusions of this study can be obtained from the corresponding author, [AZ], upon a reasonable request.

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