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Integrating TPACK and Ethnomathematics to Enhance Deep Learning in Prospective Elementary School Teachers' Numeracy Literacy

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Abstract: This study aimed to examine whether and how an instructional design integrating Technological Pedagogical Content Knowledge (TPACK) and ethnomathematics enhances numeracy and deep learning, using a modified Borg and Gall Research and Development approach followed by a non-randomized pretest-posttest quasi-experiment with 132 preservice elementary teachers, with data from a numeracy test, a deep learning engagement scale, an ethnomathematics product rubric, self-efficacy and engagement questionnaires, interviews, and reflection sheets, analyzed through analysis of covariance (ANCOVA), mediation analysis, and thematic analysis. After controlling for pretest scores, the intervention group outperformed the control group on posttest numeracy ($F(1, 129) = 18.72$, $p < .001$, $\eta p^2 = .13$; posttest means of 76.5 and 64.1), and the indirect effects through self-efficacy ($\beta = 0.21$, 95% CI [0.10, 0.33]) and engagement ($\beta = 0.18$, 95% CI [0.07, 0.29]) were statistically significant, while three qualitative themes on local culture, learning management system support, and reflection and transfer were consistent with these patterns. These findings suggest that embedding local cultural contexts within a TPACK-based instructional design is associated with stronger numeracy and deeper learning among preservice elementary teachers, and that self-efficacy and engagement are plausible mechanisms, although the non-randomized design calls for cautious interpretation.

Keywords: Deep Learning, Ethnomathematics, Numeracy Literacy, Prospective Teacher, TPACK

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INTRODUCTION

Improving numeracy literacy has become one of the central priorities of 21st-century education, particularly for prospective elementary school teachers who will serve as the front line in fostering students' mathematical competencies. According to Geiger et al. (2015), numeracy refers to the knowledge and capabilities required to meet the mathematical demands of private and public life and to participate in society as an informed and reflective citizen, although no single definition has been widely accepted. Research by Díez-Palomar et al. (2023) described numeracy as a multifaceted concept and discussed challenges for numeracy awareness in finance, health, and the critical interpretation of data. Recent work by Geiger and Schmid (2024) examined a critical turn in numeracy education and practice, which signals growing attention to the critical and social dimensions of numeracy. Drawing on lessons from international assessments, Tout (2020) traced how adult numeracy evolved from quantitative literacy, which illustrates that the construct has been shaped by both educational and assessment traditions.

Developing numeracy in classrooms depends on teachers who can convey mathematical ideas meaningfully, which places preservice teacher education at the center of this agenda. Previous work by O'Keeffe and Paige (2021) re-highlighted the potential of critical numeracy, which offers a perspective on the orientation that numeracy instruction may take. According to Suh et al. (2021), mathematical modeling can act as a catalyst for equitable mathematics instruction when teachers and young learners are prepared with twenty-first century skills. Research by Darling-Hammond et al. (2024) addressed how teachers can be educated to enact the science of learning and development, which underlines the role of teacher preparation programs in shaping classroom practice.

Attention to the depth of mathematical learning has grown across educational contexts. Research by Tanudjaya and Doorman (2020) examined higher order thinking in Indonesian lower secondary mathematics classrooms, which provides a national backdrop for the present study. In an action research study, Dolapcioglu and Doğanay (2022) used authentic learning to develop critical thinking in mathematics classes. A pedagogical study by Weng et al. (2023) addressed the promotion of students' deep learning through design-based learning.

Deep learning is closely linked to the quality of instruction and to the way learners invest in their own learning. An observation study by Sølvik and Glenna (2022) in Norwegian classrooms examined teachers' potential to promote students' deeper learning in whole-class teaching. According to Fredricks et al. (2004), engagement is a multidimensional construct comprising behavioral, emotional, and cognitive components, which offers a basis for operationalizing cognitive engagement in learning research. Recent evidence from Zhao et al. (2024) addressed whether perceived TPACK could improve deep learning, with self-regulatory learning as a mediator and technology self-efficacy as a moderator in online environments.

Technological Pedagogical Content Knowledge (TPACK) is a framework for understanding the knowledge that teachers need to integrate technology into instruction.

According to Mishra and Koehler (2006), the framework builds on Shulman's pedagogical content knowledge and describes a complex, situated form of knowledge arising from the interplay among content, pedagogy, and technology. A systematic review by Li et al. (2024) covered TPACK research in primary mathematics education, which maps how the framework has been applied at this level. Research by Bueno and Niess (2023) used a qualitative cross-case analysis with TPACK lenses to examine the redesign of mathematics preservice teachers' preparation for teaching with technology.

Previous studies have examined technology in mathematics teacher education and in student learning from several angles. Research by Saralar-Aras and Türker-Biber (2024) addressed the enhancement of prospective teachers' technological pedagogical content knowledge through mathematics lesson plan development. According to Drijvers and Sinclair (2024), digital technologies in mathematics education can be discussed in terms of their purposes and perspectives, and Poçan et al. (2023) examined the effects of mobile technology on learning performance and motivation in mathematics education. Recent evidence from Boadu and Boateng (2024) examined the mediating role of student interest in the relationships among technology integration, collaborative learning, motivation, and mathematics achievement.

Research by Mania and Alam (2021) investigated teachers' perceptions toward an ethnomathematics approach that relates mathematical concepts to learners' culture and everyday life. A study by Acharya et al. (2021) examined mathematics educators' perspectives on the cultural relevance of basic level mathematics in Nepal. Previous studies have also applied ethnomathematics in classroom teaching, for example with middle school students (Sari et al., 2023). Evidence from Averill et al. (2009) described three models of culturally responsive teaching of mathematics drawn from linked studies.

Research by Ali and Hawk (2024) used a mixed-methods design and found a significant relationship between in-service teachers' TPACK and their knowledge of students' home culture. A quasi-experimental study by Putra et al. (2025) with 39 preservice elementary teachers used a one-group pretest-posttest design and reported significant effects of project-based ethno-didactics of mathematics learning on perspectives, mathematical knowledge, and didactic knowledge. Other research has focused on in-service teachers, including the validation of a TPACK instrument for middle and high school mathematics teachers in the United States (Smith & Zelkowski, 2023) and the analysis of factors influencing digital technology use among Chinese primary mathematics educators (Li et al., 2025). A systematic review by Kadluba et al. (2025) examined how TPACK has been assessed in mathematics, with attention to its content component.

The studies reviewed above have largely addressed in-service teachers, school students, or teachers' perceptions and knowledge. Research remains limited regarding how culturally grounded instruction within a TPACK framework influences numeracy and deep learning engagement among preservice elementary teachers when compared with conventional instruction. Less attention has been directed toward psychological mechanisms such as self-efficacy, even though Wang and Zhao (2021) reported that ICT

self-efficacy mediated most effects of university ICT support on preservice teachers' TPACK in China. Evidence from Mansour et al. (2024) on factors affecting science and mathematics teachers' competencies and self-efficacy in TPACK for project-based learning and STEM suggests that self-efficacy is a relevant construct in this line of work.

This study addresses an underexplored aspect of preservice teacher education by examining a TPACK-based ethnomathematics instructional design as a means of strengthening numeracy and deep learning engagement. The aim of this study is to examine whether and how an instructional design that integrates TPACK and ethnomathematics enhances numeracy and deep learning among preservice elementary teachers. This study extends previous research by examining TPACK-based ethnomathematics instruction using a quasi-experimental comparison, a mediation analysis of self-efficacy and engagement, and a thematic analysis within the context of an Indonesian primary teacher education program. The novelty of this study therefore lies in the combined examination of a TPACK-based ethnomathematics instructional design, its association with self-efficacy and engagement, and the learning experiences that accompany it.

This study addresses three research questions. 1) Is the TPACK-based ethnomathematics instructional design associated with higher numeracy and deep learning indicators among preservice elementary teachers than conventional instruction after controlling for pretest scores? 2) To what extent do self-efficacy and engagement mediate the relationship between the instructional design and numeracy outcomes? 3) How do preservice elementary teachers experience learning with the instructional design?

METHODS

This study employed a modified Research and Development (R&D) approach based on the Borg and Gall model, combined with a quasi-experimental design to evaluate the effectiveness of a TPACK ethnomathematics-based didactic model. Chronologically, the research began with a needs analysis and the development of an initial design for the module and instructional scheme, followed by expert validation, a pilot study, and finally field implementation with treatment and control groups. The primary aim of the R&D phase was to produce a learning design that is valid, practical, and effective, while also providing insights into the mechanisms of deep numeracy learning among prospective teachers. The integration of R&D and quasi-experimental methods was chosen to ensure that the study not only developed a product but also systematically measured its impact using both quantitative and qualitative approaches.

Research Design

The quasi-experimental design employed a non-randomized pretest–posttest control group model. The sample consisted of prospective pre-service elementary school teachers students from two different cohorts, divided into treatment and control groups, with a total of approximately N = 132 participants. The treatment group received instruction using the TPACK–ethnomathematics didactic design over eight weeks, while the control group followed conventional instruction. This design enabled the researchers to compare

differences in numeracy literacy, deep learning indicators, and mediating factors such as self-efficacy and engagement across the two groups. The design follows best practices in R&D-based educational research and quasi-experimental methodology.

Research Instruments

This study employed four instruments to collect quantitative and qualitative data. First, the Numeracy Literacy Test, administered as a pretest and posttest, consisted of 30–40 multiple-choice and open-ended items designed to assess students' conceptual understanding, problem-solving abilities, and knowledge transfer skills. The construct validity of the test was examined through expert panel review, while its internal consistency reliability was evaluated using Cronbach's alpha. The reliability results of the Numeracy Literacy Test are presented in Table 1.

Table 1. The Internal Reliability of the Numeracy Literacy Test

No	Indicator	Value
1	Number of Items	35
2	Cronbach's Alpha	0.812
3	Mean Item Difficulty	0.57
4	Mean Item Discrimination	0.42

Second, the Deep Learning Engagement Scale was used to measure students' engagement in the learning process, focusing on cognitive engagement, metacognitive reflection, and knowledge transfer. The scale was adapted from existing instruments and subjected to expert review to establish content validity. Third, the Ethnomathematics Product Rubric was developed to assess the quality of students' products, particularly their incorporation of local cultural contexts into mathematical learning. Finally, self-efficacy and engagement questionnaires, complemented by semi-structured interviews, were employed to explore students' perceptions of the learning experience and the implementation of the instructional design. Together, these instruments provided complementary evidence of students' numeracy literacy development, learning engagement, product quality, and perceptions of the learning process.

Research Procedures

The research was conducted through five sequential stages. First, the researchers conducted a needs analysis and preliminary data collection through classroom observations, interviews with lecturers in the Pre-service elementary school teachers program, and a literature review focusing on Technological Pedagogical Content Knowledge (TPACK), ethnomathematics, and deep numeracy learning. The findings from this stage informed the development of an instructional design aligned with the learning needs and contextual characteristics of the students.

Second, the didactic design was developed by preparing a digital learning module or Learning Management System (LMS) and an instructional scheme integrating TPACK principles, ethnomathematical contexts, and numeracy learning standards. Third, the proposed design underwent expert validation involving specialists in mathematics

education and educational technology. The validation focused on content relevance, instructional quality, and technological integration, with content validity assessed using the Content Validity Index (CVI).

Fourth, a pilot study was conducted with a small group of students to evaluate the feasibility of the learning module and research instruments, including implementation time and item difficulty. Revisions were made based on the pilot study findings before the main implementation. Finally, the validated instructional design was implemented over eight weeks in treatment and control groups. The study collected quantitative data, including tests and questionnaires, alongside qualitative data from interviews and student reflections. The integration of these data sources enabled an examination of learning outcomes and students' experiences throughout the intervention. The overall sequence of the research procedures is presented in Figure 1.

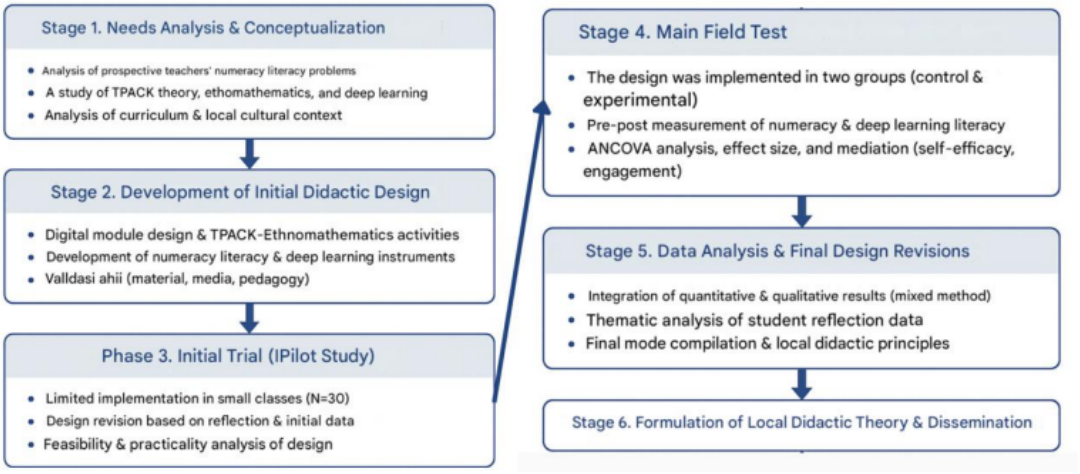


Figure 1. Research flow of the TPACK-Ethnomathematics study

Data Analysis

Data were analyzed using quantitative and qualitative approaches to provide a comprehensive understanding of the effectiveness of the developed didactic design. Quantitative analysis involved assessing instrument reliability using Cronbach's alpha and examining construct validity through exploratory factor analysis (EFA) or confirmatory factor analysis (CFA), where appropriate. Differences in pretest and posttest outcomes between the treatment and control groups were examined using analysis of covariance (ANCOVA) or multivariate analysis of covariance (MANCOVA), as appropriate, with pretest scores included as covariates. The results were reported using p-values, confidence intervals, and effect sizes, including Cohen's d. Mediation analysis was also conducted to explore the potential roles of self-efficacy and learning engagement in the relationship between the instructional intervention and numeracy literacy outcomes.

Qualitative data from semi-structured interviews and student reflection sheets were analyzed using thematic analysis following Braun and Clarke's approach. Two independent coders examined the data, and inter-coder agreement was assessed using

Cohen's kappa. The qualitative findings were integrated with the quantitative results to provide deeper insights into students' learning processes and the role of ethnomathematical contexts in supporting numeracy literacy development.

Research Ethics

This study obtained ethical approval from the educational ethics committee. All participants provided informed consent before data collection. Privacy and confidentiality were ensured through respondent anonymization, and data triangulation was applied to strengthen the validity of the findings.

RESULTS

Numeracy Literacy and Deep Learning

This section presents the findings regarding the effectiveness of the TPACK-ethnomathematics-based didactic design in improving numeracy literacy among prospective elementary school teachers. The analysis focused on differences in pretest and posttest performance between the treatment and control groups, as well as changes in deep learning indicators, including cognitive engagement, metacognitive reflection, and knowledge transfer.

Table 2. The Pretest and Posttest Numeracy Literacy Scores

Group	Pretest Mean ± SD	Posttest Mean ± SD	Δ Mean
Treatment	58.3 ± 8.2	76.5 ± 7.4	18.2
Control	57.9 ± 7.9	64.1 ± 8.1	6.2

As presented in Table 2, the ANCOVA results revealed a statistically significant difference in posttest numeracy literacy scores between the treatment and control groups after controlling for pretest performance, $F(1, 129) = 18.72$, $p < .001$, $\eta^2 = .13$. This finding indicates that the didactic design had a significant effect on students' numeracy literacy outcomes. Furthermore, the treatment group achieved a higher mean gain score ($M = 0.44$) than the control group ($M = 0.16$), suggesting greater improvement following the intervention.

The analysis also indicated significant improvements in the treatment group across the three deep learning indicators: cognitive engagement, metacognitive reflection, and knowledge transfer ($p < .05$). These findings suggest that integrating technology, pedagogical strategies, mathematical content, and local cultural contexts may support both numeracy literacy development and deeper learning processes. This interpretation is consistent with previous research highlighting the potential of technology-enhanced, culturally contextualized learning to strengthen students' conceptual understanding (W. Li et al., 2023).

The Mediating Roles of Self-Efficacy and Student Engagement

The mediation analysis conducted using the PROCESS macro indicated that self-efficacy played a significant mediating role in the relationship between the TPACK-ethnomathematics intervention and numeracy literacy outcomes. The indirect effect was statistically significant ($\beta = 0.21$, 95% CI [0.10, 0.33], $p < .01$), suggesting that students' confidence in their numeracy learning abilities may contribute to the effectiveness of the instructional intervention. Students with stronger self-efficacy may be better positioned to engage with challenging mathematical tasks and benefit from culturally contextualized learning experiences. This finding is consistent with previous studies highlighting the importance of self-efficacy in supporting learning outcomes (Kadluba et al., 2025; Mansour et al., 2024).

Student engagement also emerged as a significant mediator, with an estimated indirect effect of $\beta = 0.18$ (95% CI [0.07, 0.29], $p < .05$). Qualitative findings complemented this result, as students reported more meaningful learning experiences when mathematical concepts were connected to local cultural contexts and delivered through the Learning Management System (LMS). These experiences appeared to encourage active participation, reflection, and the application of mathematical knowledge to real-world situations. The findings align with deep learning frameworks that emphasize contextual understanding, metacognitive reflection, and knowledge transfer as essential dimensions of meaningful learning (Priyanda et al., 2025; Santosa et al., 2025). Taken together, these results suggest that self-efficacy and student engagement are potential mechanisms through which the TPACK–ethnomathematics-based didactic design supports numeracy literacy development.

Qualitative Findings and Learning Mechanism

Thematic analysis of interview data and student reflections revealed three major themes that provide insights into students' learning experiences during the implementation of the TPACK-ethnomathematics-based didactic design. The first theme concerned the connection between local culture and mathematical concepts. Students reported that concepts such as fractions and decimals became easier to understand when contextualized through familiar cultural practices, including batik patterns and traditional trading systems. These connections helped students relate abstract mathematical concepts to everyday experiences and recognize the relevance of numeracy in their cultural environment.

The second theme highlighted the role of the Learning Management System (LMS) and educational technology in supporting learning engagement. Interactive learning modules, opportunities to revisit instructional materials, and online discussion forums provided students with flexible ways to access content and participate in learning activities. These features appeared to support students' motivation and sustained engagement throughout the learning process.

The third theme focused on reflection and knowledge transfer. Student reflections and interview responses indicated that students could apply previously learned numeracy concepts to unfamiliar problems, suggesting the development of conceptual understanding

beyond routine tasks. Taken together, these qualitative findings complement the quantitative results by illustrating how the integration of TPACK and ethnomathematics may support numeracy literacy, contextual understanding, and reflective learning. These findings are consistent with previous studies emphasizing the value of culturally relevant and technology-supported mathematics learning (Acharya et al., 2021; Dare et al., 2021; Machaba & Dhlamini, 2021).

DISCUSSION

Instructional Design Effects on Numeracy and Deep Learning

The intervention group achieved higher posttest numeracy than the control group after adjustment for pretest scores ($F(1, 129) = 18.72$, $p < .001$, $\eta p^2 = .13$), with mean gains of 18.2 points and 6.2 points, respectively. This pattern may reflect the way the design linked fractions and decimals to *batik* patterns and traditional trading systems and supported them with digital learning resources, which gave participants repeated opportunities to interpret mathematical ideas in familiar situations. Previous research by Putra et al. (2025) reported significant effects of an ethnomathematics-based project approach on preservice elementary teachers' mathematical knowledge, although their one-group design and outcome measures differ from the controlled comparison used here. Evidence from Kadluba et al. (2025) on how the content component is assessed in TPACK research is relevant because the numeracy test in this study provides a direct content-related outcome, and the observed gains should be interpreted in relation to that measure.

Taken together with the improvement in cognitive engagement, metacognitive reflection, and knowledge transfer, the findings indicate that the design is associated with change in both test performance and the learning processes behind it. This interpretation is compatible with the work of Weng et al. (2023) on design-based learning as a route to deep learning and with the observation study by Sølvik and Glenna (2022), which addressed teachers' potential to promote deeper learning in whole-class teaching. Research by Li et al. (2023) examined metacognition teaching in collaborative programming learning, and its different domain should be considered when relating it to the metacognitive reflection indicator used here. For teacher educators, these results imply that numeracy courses may benefit from tasks that couple cultural contexts with structured reflection and transfer problems, although the size of the effect should be verified with other cohorts.

Self-Efficacy and Engagement as Mediating Mechanisms

Self-efficacy ($\beta = 0.21$, 95% CI [0.10, 0.33]) and engagement ($\beta = 0.18$, 95% CI [0.07, 0.29]) both showed significant indirect effects on numeracy, which indicates two statistical pathways linking the intervention with the outcome. A plausible explanation is that familiar contexts supported participants' confidence in handling numeracy tasks, while the interactive LMS activities sustained participation, and both processes may have contributed to progress. Research by Wang and Zhao (2021) found that ICT self-efficacy mediated most effects of university ICT support on preservice teachers' TPACK, which shows that self-efficacy can operate as a pathway in teacher education settings even though

their outcome was TPACK and the present outcome is numeracy. Different roles have been reported in Zhao et al. (2024), where technology self-efficacy functioned as a moderator and self-regulatory learning as a mediator between perceived TPACK and deep learning, and this variation may be associated with differences in constructs, outcomes, and online learning contexts.

Recent evidence from Boadu and Boateng (2024) on the mediating role of student interest between technology integration, collaborative learning, motivation, and mathematics achievement is compatible with the mediating role of engagement observed here. According to Fredricks et al. (2004), engagement is multidimensional, so the engagement measures used in this study, which emphasize cognitive engagement, metacognitive reflection, and knowledge transfer, capture a particular portion of that construct. The mediation results are best interpreted as statistical pathways consistent with the intervention effect, because the non-randomized design limits causal claims. Given that Mansour et al. (2024) examined factors affecting teachers' self-efficacy in TPACK for project-based learning and STEM, lecturers may consider monitoring self-efficacy alongside numeracy outcomes and including confidence-building and participation-oriented activities.

Cultural Contexts and Technology as Learning Mechanisms

The qualitative analysis produced three themes concerning local culture and mathematical concepts, LMS-supported engagement, and reflection and knowledge transfer. Familiar practices such as *batik* patterns and traditional trading systems appear to have given participants concrete referents for fractions and decimals, while LMS features allowed them to revisit materials and discuss ideas online. Research by Ali and Hawk (2024) reported a significant relationship between in-service teachers' TPACK and their knowledge of students' home culture, which supports attention to cultural context within TPACK. Different cultural resources may be relevant in other settings, as suggested by Averill et al. (2009), who described three models of culturally responsive mathematics teaching, and by Acharya et al. (2021), who examined educators' perspectives on cultural relevance in Nepal.

According to Polly (2024), TPACK can be enacted with different learning technologies in elementary mathematics, and school culture and context influence whether and how teachers integrate technology. Evidence from Li et al. (2025) on factors influencing digital technology use among Chinese primary mathematics educators and from Payadnya et al. (2025) on cultural integration in AI-enhanced mathematics education among Southeast Asian educators points to the relevance of contextual and cultural conditions for digital tool use. Together with the present findings, this evidence suggests that the LMS contributed within a specific cultural and institutional context, and results may vary where connectivity, platform design, or cultural resources differ. Teacher educators can therefore adapt the cultural examples to local practices and check that the digital environment supports discussion, revisiting of materials, and reflection.

Theoretical and Practical Implications

Theoretically, the results extend TPACK research by adding cultural context and psychological mediators to a framework that Mishra and Koehler (2006) described as an interplay among content, pedagogy, and technology. A structural equation modelling analysis by Li and Li (2024) examined TPACK components in technology integration in mathematics education, and the present mediation results add self-efficacy and engagement as variables linking instruction with learning outcomes. Research by Priyanda et al. (2025) examined teachers' pedagogical reasoning in mathematics using the TPACK framework, and the reflective themes identified here suggest that reflection may be one route for developing such reasoning among preservice teachers. These interpretations remain tentative because they derive from one program and a single instructional design.

According to Rakes et al. (2022), TPACK is connected with effective teaching practices when mathematics is taught with technology, which supports embedding technology tasks in course activities that model such practices. Work by Darling-Hammond et al. (2024) on educating teachers to enact the science of learning and development and by Suh et al. (2021) on preparing teachers with twenty-first century skills indicates that teacher preparation is a recurring concern, and the present design offers an example of culturally grounded, technology-supported numeracy tasks. Lecturers can use the module structure, LMS activities, and ethnomathematics product rubric to plan comparable courses, and curriculum developers can consider the evidence when revising numeracy learning outcomes. Expectations should remain realistic because pedagogical choices differ across higher education contexts, as the review by Albeshree et al. (2022) of mathematics teaching pedagogies for tertiary engineering and information technology students suggests.

Limitations and Directions for Future Research

This study has several limitations that should be considered when interpreting the findings. The non-randomized assignment of participants from two cohorts leaves open the possibility of preexisting differences, although the ANCOVA controlled for pretest scores. The eight-week implementation did not include a delayed posttest, so the persistence of the observed gains remains unknown, and the engagement and self-efficacy measures relied on self-report. The participants came from a single primary teacher education program, and the qualitative themes reflect the views of those participants, so transferability to other institutions and cultural settings should be examined carefully.

Future research could employ randomized or multi-site designs and delayed posttests to test the durability and generalizability of the effects. Validation work such as that of Smith and Zelkowski (2023), who developed a TPACK instrument for in-service middle and high school mathematics teachers, suggests that comparable instruments for preservice populations and for deep learning assessment would strengthen measurement. A conceptual exploration by Dolgopolovas and Dagiene (2024) of competency-based TPACK approaches for computational thinking and integrated STEM suggests that the design could be extended to interdisciplinary competencies. Adaptation of the design for

use with elementary students and longitudinal studies of its sustained impact would clarify how far the benefits extend into classroom practice.

CONCLUSION

This study examined whether and how a TPACK-based ethnomathematics instructional design enhances numeracy and deep learning among preservice elementary teachers. Participants in the intervention group achieved higher posttest numeracy than the control group after adjusting for pretest scores, and the three deep learning indicators improved significantly in the intervention group. Self-efficacy and engagement showed significant indirect effects, which indicates that these variables are statistical pathways consistent with the observed improvement. Interview and reflection data described three themes involving local culture, LMS-supported participation, and reflection and transfer.

The results offer lecturers and curriculum developers evidence-informed guidance for designing numeracy modules that combine cultural contexts, technology, and reflective tasks. Because the study used a non-randomized design in a single program, the conclusions apply to comparable preservice contexts and should be tested further. Future studies may use randomized or multi-site designs, delayed posttests, and refined assessment instruments for deep learning. Adapting the design for use with elementary students and examining longer-term outcomes would clarify how far the benefits extend into classroom practice.

AI Use Statement

The authors used AI tools, if applicable, solely for language editing and proofreading. All authors take full responsibility for the content of this manuscript.

Author Contributions

W: contributed to conceptualization, methodology, and supervision. IR: contributed to instructional design and manuscript review. RKH: contributed to data collection and analysis. P: contributed to data analysis and manuscript revision. ZA: contributed to the development of the instructional design and validation of learning materials. AYP: contributed to data collection, qualitative analysis, and manuscript drafting. All authors reviewed and approved the final manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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