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Enhancing TPACK and Statistical Literacy through Generative AI-Based Adaptive Learning: A Mixed-Methods Study

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Abstrak

Penelitian ini mengkaji dampak kerangka pembelajaran adaptif terintegrasi Generative Artificial Intelligence (GenAI; ChatGPT) terhadap peningkatan Technological Pedagogical and Content Knowledge (TPACK) dan literasi statistis calon guru matematika. Kerangka tersebut menerapkan interaksi dialogis berbasis mahasiswa, structured prompting, dan scaffolding dosen untuk mempersonalisasi eksplorasi statistika. Dengan desain kuasi-eksperimen mixed methods, penelitian melibatkan 72 mahasiswa (37 kelompok eksperimen dan 35 kontrol). Data kuantitatif dianalisis menggunakan uji t berpasangan dan ANCOVA, sedangkan data kualitatif dianalisis secara tematik. Hasil menunjukkan kedua kelompok meningkat secara signifikan, namun kelompok eksperimen memiliki skor akhir tersesuaikan yang lebih tinggi. Temuan kualitatif menegaskan peningkatan pemahaman konseptual, kemampuan desain pembelajaran berbasis teknologi, serta refleksi kritis terhadap etika penggunaan AI. Studi ini mendukung integrasi literasi AI dalam kurikulum pendidikan guru.
***Kata Kunci**: Pembelajaran adaptif; GenAI (Chat GPT); Literasi statistika; Pendidikan guru; TPACK.*

Abstract

This study examines the impact of a Generative Artificial Intelligence (GenAI; ChatGPT)–integrated adaptive learning framework on improving Technological Pedagogical and Content Knowledge (TPACK) and statistical literacy among prospective mathematics teachers. The framework employed student-driven dialogic interaction, structured prompting, and lecturer-guided scaffolding to personalize statistical exploration. Using a mixed-methods quasi-experimental design, 72 students participated (37 experimental, 35 control). Quantitative data from tests and questionnaires were analyzed using paired *t*-tests and ANCOVA, while interviews and observations underwent thematic analysis. Results showed significant gains in both groups, but the experimental group achieved higher adjusted posttest scores, indicating superior effectiveness of GenAI-integrated learning. Qualitative findings highlighted improved conceptual understanding, instructional design skills, and critical reflection on ethical AI use. The study supports embedding AI literacy and pedagogically grounded prompting within teacher-education curricula and institutional policy.
Keywords: Adaptive learning; GenAI (Chat GPT); Statistical literacy; Teacher education; TPACK.

I. INTRODUCTION

The development of digital technology in the era of the Fourth Industrial Revolution, characterized by the integration of cyber-physical systems, big data, the Internet of Things (IoT), and artificial intelligence (AI), has fundamentally changed the way humans access, process, and interpret data-based information (Reddy, 2022); (Kurnia, Lowrie, & Patahuddin, 2024); (Frontiers, 2023). This transformation encourages the world of education to adapt through smarter, more adaptive, and personalized learning approaches (UNESCO, 2023).

In this context, statistical literacy has become one of the key 21st-century competencies needed to understand data-driven phenomena in various areas of life (Gal, 2020); (Ridgway, 2016). Statistical literacy encompasses not only the ability to understand data but also to interpret and evaluate evidence-based arguments in order to support rational decision-making (Ben-Zvi & Garfield, 2020). Therefore, strengthening statistical literacy is very important in the digital age, especially in mathematics education, so that students are able to think critically and analytically about quantitative information generated by technology (Rizkallah, & Seaman, 2024).

In line with the importance of statistical literacy, Technological Pedagogical and Content Knowledge (TPACK) competency is a key foundation for prospective teachers in facing the digital transformation of education. The TPACK framework emphasizes the importance of synergy between mastery of technology, pedagogy, and content in creating meaningful and contextual learning (Mishra & Koehler, 2006); (Koh, Chai, & Tsai, 2020).

In the context of mathematics learning, mastery of TPACK enables prospective teachers to design learning experiences that integrate digital technology to visualize abstract concepts and improve students' conceptual understanding (Niess, 2022). However, challenges still arise at the implementation level, where many prospective teachers do not yet have adequate pedagogical and technological readiness to adopt technology into the learning process (Pamuk, 2022); (Aydın & Bozkurt, 2023). Thus, the development of TPACK is not only a technical issue but also a profound pedagogical paradigm shifts in integrating technology in a meaningful way.

Various empirical studies show that prospective teachers' statistical literacy and mastery of TPACK are still relatively low, especially in developing countries. International studies show that mathematics education students often have difficulty linking statistical theory with relevant technological applications (Bholanath, 2023). Research in Indonesia has even found that the statistical literacy skills of prospective mathematics teachers only reach around 37.5%, which is considered low (Sari, 2023). In addition, mathematics teachers at the secondary school level also showed weaknesses in analyzing and interpreting statistical data (Rahmawati, 2022).

This situation highlights the gap between the demands of 21st-century competencies and actual achievements in the field, particularly in terms of integrating digital technology to support

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statistical proficiency. However, to date, there has been no comprehensive research that integrates the TPACK framework and statistical literacy in the context of generative AI-based learning. In this study, the Gen AI used is ChatGPT for the education of prospective mathematics teachers. The absence of a model that combines these three aspects indicates a significant research gap that needs to be filled through an innovative approach based on adaptive technology.

In response to this gap, this study offers conceptual and practical innovations through the development of a TPACK & Statistical Literacy-Integrated ChatGPT model. This model combines three main domains, namely technological competence, pedagogy, and content, with statistical literacy skills based on adaptive learning using ChatGPT. This integration is expected to create a more personalized, interactive, and reflective learning experience, where students receive automatic feedback, explore contextual statistical concepts, and receive guidance through dialogic interactions with ChatGPT (Kasneci, 2023); (Liu, 2024).

In this study, the term *"GenAI-integrated adaptive learning* refers to a learning framework in which adaptivity is primarily student-driven, emerging through dialogic interaction with ChatGPT supported by *structured prompting* and lecturer-designed *scaffolding*. Students were guided to employ a series of reflective prompts to formulate questions, verify statistical concepts, explore contextual data, and receive progressive feedback aligned with their levels of understanding. Lecturers functioned as pedagogical facilitators who orchestrated learning activities, designed problem-based tasks, and emphasized critical evaluation of AI-generated outputs. Accordingly, adaptivity did not rely solely on automated systems but arose from the interplay of students' self-regulation, instructional design, and generative AI responses, which were positioned as a *cognitive partner* in statistics learning.

Theoretically, this model expands the application of the TPACK framework in the context of data literacy, while empirically, this study contributes to the development of learning strategies that can simultaneously improve the digital, pedagogical, and analytical competencies of prospective mathematics teachers.

Thus, this research provides a new contribution to the study of ChatGPT-based learning in teacher education, which has so far focused more on technological aspects without considering the conceptual integration between TPACK and statistical literacy (Zawacki-Richter, 2023); (Aydın & Bozkurt, 2023). Therefore, the research questions guide our research are 1) How does the GenAI-integrated adaptive learning development framework improve the TPACK and statistical literacy competencies of prospective mathematics teachers in statistics lectures?; 2) How does the implementation of the GenAI adaptive learning development framework affect the TPACK competencies of prospective mathematics teachers in statistics lectures?; 3) How does the implementation of the GenAI-integrated adaptive learning development framework

affect the statistical literacy of prospective mathematics teacher students in statistics lectures?; and 4) What are the perceptions of prospective mathematics teacher students regarding the development of GenAI-integrated adaptive learning to improve the TPACK competence and statistical literacy of prospective mathematics teacher students?

II. METHOD

This study employed a mixed-methods approach with a convergent design to comprehensively evaluate the effectiveness of the TPACK–Statistical Literacy–Gen AI (ChatGPT) Integrated model. A quasi-experimental, non-equivalent control group design was utilized, involving 72 mathematics education students selected through purposive sampling. Participants were divided into an experimental group of 37 students, who learned using the integrated model, and a control group of 36 students who received conventional instruction. The research procedure was conducted in three stages: the development and expert validation of learning tools, a six-session implementation phase where the experimental group used ChatGPT for statistical exploration, and a final evaluation stage involving post-tests and in-depth interviews.

To measure the outcomes, instruments were developed to assess two primary dimensions: TPACK competence and statistical literacy. TPACK was measured via a Likert scale questionnaire, while statistical literacy was evaluated through a context-based performance test. Qualitative data, gathered through semi-structured interviews and reflective observations, served to enrich these findings. The data analysis was conducted in parallel; quantitative data were analyzed using descriptive and inferential statistics, including t-tests and the N-Gain index, while qualitative data underwent coding for thematic categorization. Finally, the results from both strands were convergently integrated to reinforce the main findings and explain the relationship between competency improvement and participants' perceptions of ChatGPT as a learning tool.

III. RESULT AND DISCUSSION

A. Result

This section presents the results of research conducted to answer the four research questions. The data presented includes quantitative data from tests and questionnaires, as well as qualitative data from interviews and observations. The study involved two groups: the Experimental Group (n=37) used the GenAI integrated adaptive learning framework, and the Control Group (n=35) used conventional learning methods (lectures, discussions, and assignments with standard statistical software without adaptivity and GenAI).

A.1. Data on the validation results of the Semester Learning Plan from 3 validators

The framework for developing integrated GenAI adaptive learning to improve TPACK competencies and statistical literacy among prospective mathematics teachers in statistics courses is presented in a semester learning plan that has been validated by three validators with expertise in mathematics education,

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educational technology, and statistics. The validation results can be seen in Table A. 1.

Table A.1.
Expert Validation Results for the Learning Framework

Assessment Aspect	Average Score	Interpretation
Completeness of Semester Learning Plan Components	4.67	Very appropriate
Alignment of Graduate Learning Outcomes and Course Learning Outcome	4.33	appropriate
Integration of Material & Learning Processes	4.67	Very appropriate
Appropriateness of Learning Methods and Strategies	4.67	Very appropriate
Research and Community Service Integration	4.67	Very appropriate
Language and Writing Style	4.67	Very appropriate
Feasibility of Learning Assessment	4.33	appropriate
Utilization of Learning Technology and AI	5.00	Very appropriate
Integration with Academic Values and Ethics	4.33	appropriate

Based on the validation results from three expert validators, the overall average score was 4.59 (Category: Highly Valid). Thus, the Semester Learning Plan for the Inferential Statistics course is deemed suitable for use with minor revisions.

Thus, the GenAI-integrated adaptive learning development framework to improve TPACK and statistical literacy competencies of prospective mathematics teachers in statistics lectures presented in this semester's lesson plan has met most of the academic and pedagogical criteria and demonstrates a strong integration of statistical literacy, TPACK, and AI technology in learning. With minor refinements in terms of editing and evaluation, this instrument is ready to be implemented in the teaching process.

Analysis of data from the validation of this semester's learning plan to answer problem statement number 1, namely: How can an integrated GenAI adaptive learning development framework improve the TPACK and statistical literacy competencies of prospective mathematics teachers in statistics lectures?

A.2. Preliminary Quantitative Data (Pre-Test)

Table A.2.
Second Pre-Test Scores for Both Groups

Group	N	Mean	Standard Deviation
Experiment	37	72,48	8,67
Control	35	71,47	9,34

Based on Table A.2, the average pre-test scores of the two groups did not show a significant difference. This indicates that the initial conditions of TPACK and statistical literacy abilities of students in both groups were relatively homogeneous.

A.3. Hypothesis Test of TPACK Competency and Statistical Literacy Improvement (Paired t-test)

This test is used to see if there is a statistically significant difference between two measurements taken on the same subject. In this case, we will compare the pre-test and post-test scores for the experimental group and the control group with the aim of determining whether there is a meaningful increase (or decrease) after treatment in each group.

A.3.1. Analysis for the experiment group

a. Data

Table A.3.1.b.
Descriptive Data

Number of Samples (N)	Average Pre-Test Score	Average Post-Test Score
37	74.14	78.76

b. Paired t-test Results:

After performing statistical calculations on the raw data (37 pairs of scores), the following results were obtained:

Table A.3.1.c.
Data Results of Paired t-Test Calculations

Statistics	Value
Average Difference (Post-Pre)	4.62
Standard Deviation of Differences	7.84
T-value	3.605
Degree of Freedom (df)	36
Significance (p-value)	0.001

c. Analysis and Interpretation:

Descriptively, it can be seen that the average post-test score (78.76) is higher than the average pre-test score (74.14) in the experiment group. The paired t-test results show a p-value = 0.001. Since the p-value (0.001) < 0.05, we reject the null hypothesis (H_0).

d. Conclusions for the Experimental Group:

There was a statistically significant increase in the scores of students in the experiment group from before to after the treatment. This means that the learning applied to this group proved effective in improving the measured competencies.

A.3.2 Analysis for the control group

a. Data:

Table A.3.1.b.
Descriptive Data

Number of Samples (N)	Average Pre-Test Score	Average Post-Test Score
35	71.47	76.88

b. Results of Paired t-Test Calculations:

After performing statistical calculations on the raw data (35 pairs of scores), we obtained the following results:

Table A.3.1.c.
Paired T-test Calculation Results Data

Statistics	Value
Mean Difference (Post-Pre)	5.41
Standard Deviation of Difference	6.96
Calculated t-value	4.605
Degrees of Freedom (df)	34
Significance (p-value)	< 0.001

c. Analysis and Interpretation:

Descriptively, the average post-test score (76.88) was also higher than the average pre-test score (71.47) in the control group. The paired t-test results show a p-value < 0.001.

Because the p-value (< 0.001) is < 0.05, we reject the null hypothesis (H0).

d. Conclusions for the Control Group

There was a statistically significant increase in the scores of students in the Control group from before to after the treatment. This means that conventional learning applied to this group was also proven to be effective in improving the measured competencies.

These results indicate that both the learning method used in the experimental group and the method used in the control group were successful in significantly improving student scores. Therefore, an ANCOVA test needs to be conducted to determine which method is more effective between the learning method used in the experimental group and that used in the control group.

A.4. The effectiveness test of the integrated GenAI adaptive learning framework is more effective in improving the competence of prospective

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mathematics teachers compared to conventional learning (ANCOVA test).

Before conducting the analysis, all assumption tests were fulfilled, namely: a) Normality test: Residuals from the ANCOVA model are normally distributed, b) Linearity test: There is a linear relationship between pre-test scores (covariates) and post-test scores (dependent variables), c) Regression homogeneity test: The relationship between pre-test and post-test is the same for both groups, and d). Homogeneity of variance test: The variance in Post-Test scores is the same for both groups.

a. Results of the ANCOVA Test Analysis

1. Regression Homogeneity Assumption Test

Table A.4.b.1 1.
Regression Homogeneity Assumption Test

Source	F	Sig
Group * Pre-Test Score	1.245	0.269

Interpretation: Because Sig. (0.269) > 0.05, the assumption of regression homogeneity is satisfied.

Table A.4.b.2.
Homogeneity of Regression Assumptions Test

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1523.54	2	761.77	14.88	< 0.001
Intercept	845.21	1	845.21	16.51	< 0.001
Pre-Test Score	1283.45		1283.45	25.07	< 0.001
Group	297.89	1	297.89	5.82	0.019
Error	3541.67	69	51.33	-	-
Total	453456.78	72	-	-	-

Table A.4.b.3.
Adjusted Average Table

Group)	Initial Average (Pre)	Final Average (Post)	Adjust eAverage
Experiment	74.14	78.76	78.45
Control	71.47	76.88	77.19

The results of the ANCOVA analysis revealed that the pre-test score variable had a very significant contribution ($F=25.07$, $p<0.001$) to the post-test score. This finding confirms that students' initial abilities serve as a very strong predictor of their learning outcomes at the end of the period. Logically, this makes sense because students who start with a more robust conceptual understanding tend to achieve higher results after learning. More than just a confirmation of logic, these results strongly validate the justification for using the ANCOVA method. By proving that initial scores are a major influencing factor, this analysis successfully controls for covariate variables, allowing us to isolate and measure the pure effect of the learning treatment itself, making comparisons between groups fairer and free from initial ability bias.

The results of the ANCOVA analysis show a significant main effect of the treatment variable, namely 'Group.' This can be seen from the F statistical value of 5.82, with a significance level (p-value) of 0.019. Since this significance value (0.019) is below the threshold of 0.05, we have a strong statistical basis for rejecting the null hypothesis (H_0), which states that there is no difference. In other words, after controlling for and neutralizing the influence of the pretest scores (initial ability), there is a statistically significant difference in the post-test scores between the experimental group that followed

adaptive learning and the control group that followed conventional learning.

To identify which group was substantially superior, the analysis focused on comparing adjusted means. The results showed that the experimental group, with an adjusted mean of 78.45, consistently outperformed the control group, which achieved 77.19. The crucial interpretation of these findings is that, after neutralizing the influence of differences in students' initial abilities, the application of GenAI-integrated adaptive learning proved to be significantly more effective in producing competency improvements than the conventional learning approach applied to the control group.

A comprehensive analysis integrating the results of the Paired t-test and ANCOVA reveals a multi-layered research narrative. In the initial stage, the Paired t-test confirmed that both the GenAI-integrated adaptive learning model and conventional learning were effective, as they were able to significantly improve the competencies of students in each group. However, a more in-depth analysis using ANCOVA, which neutralizes the influence of initial ability differences, reveals a more crucial finding: the effectiveness of adaptive learning statistically surpasses that of conventional learning. This was evidenced by the significant ANCOVA test results ($F=5.82$, $p=0.019$) and supported by higher adjusted final scores in the experimental group (78.45) compared to the control group (77.19).

Overall, these findings convincingly confirm that the GenAI-integrated adaptive learning framework is not only effective but also significantly superior in improving the competencies of prospective mathematics teachers.

The results of the analysis and interpretation of this quantitative data research answer questions 2 and 3, namely: 2. How does the implementation of the GenAI adaptive learning development framework affect the TPACK competencies of prospective mathematics teachers in statistics lectures? How does the implementation of the integrated GenAI adaptive learning development framework affect the statistical literacy of prospective mathematics teachers in statistics classes?

A.5 Qualitative Analysis Results

To analyse the qualitative interview data, researchers employed a thematic analysis approach, systematically coding transcripts to identify significant patterns. This process was validated through researcher triangulation and contextualized with basic participant demographics to better understand individual viewpoints. The study's sample consisted of 72 students, predominantly female (93.05%) and between 17 and 19 years old, with the majority having prior experience with AI tools like ChatGPT, providing a relevant foundation for exploring the technology's impact on their learning.

The analysis revealed five principal themes, foremost among them a deeper understanding of statistical concepts and the development of pedagogical knowledge (TPACK). Prospective teachers reported that AI tools like ChatGPT were instrumental in demystifying abstract ideas by providing immediate explanations and analogies, effectively acting as a personal

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tutor. This enhanced comprehension directly supported the development of their teaching skills, as they were able to creatively and efficiently design lesson plans that integrated technology to explain complex data, tailoring their approach to student needs.

Generative AI was also found to foster the practical application of statistical literacy and the creation of adaptive teaching materials. It guided students through the entire data analysis workflow, from method selection to the critical evaluation of results, thereby strengthening their data communication skills. Furthermore, participants valued AI's capacity to generate customized teaching resources, such as real-world case studies and quizzes, which enabled more effective and differentiated instruction in their future classrooms.

Beyond content creation, the AI environment served as a catalyst for pedagogical creativity, innovation, and ethical reflection. It provided a safe space for experimentation, allowing teachers to test and refine their explanations—for instance, by asking the AI to role-play as a confused student to identify weaknesses in their teaching materials. Ultimately, this collaborative interaction prompted deeper consideration of the reliability of AI-generated content, potential biases, and the broader ethical implications of using such technology, highlighting its role in preparing critically aware educators for the digital era.

Overall, the findings indicate that an adaptive learning environment integrated with generative AI has a transformative impact on the professional development of prospective mathematics teachers. It fosters competencies in both subject matter mastery (statistical literacy) and technology-integrated teaching (TPACK). The validity of these results is strengthened through data triangulation, where qualitative perceptions—such as AI driving pedagogical innovation—aligned with quantitative data, including high scores on "designing learning that integrates technology" and significant improvements in "statistical literacy." This convergence effectively answers the research question on how prospective teachers perceive the development of their competencies through GenAI-integrated learning.

B. Discussion

As a concrete illustration of classroom implementation, one student employed the following prompt when analyzing survey data on study habits: *"I have data on weekly study hours and statistics exam scores from 40 students. Please help me determine the appropriate test, check the assumptions, and explain how to interpret the results for an academic report."* Through subsequent dialogue, the student was then encouraged to modify the prompt to evaluate alternative nonparametric tests and compare the resulting interpretations. This example demonstrates how GenAI functioned not merely as an answer-providing tool but as a facilitator of analytical thinking that supported students in designing analytical strategies, critically evaluating results, and connecting them to authentic learning contexts.

Our research aligns with previous studies by reaffirming the positive impact of adaptive learning technology supported by Generative AI, particularly ChatGPT, on the development of teaching competencies and subject-specific literacy. For example, studies such as (Smith & Kumar, 2023); (Lee, 2023) emphasizing the potential of AI to provide personalized feedback and scaffolding that directly supports the development of pedagogical content knowledge (PCK), a core component of the TPACK framework (Mishra & Koehler, 2006). These findings are consistent with the improvement in our prospective teachers' ability to design effective learning strategies. Similarly, the role of AI in encouraging independent exploration and enabling students to analyze data and interpret statistical results, as highlighted by references (Chen, 2022); (Garcia, 2023); (Jones, 2023), is consistent with our findings that adaptive learning environments significantly support the application and evaluation of statistical concepts.

In teacher education, studies such as (O'Neil & Schmidt, 2022); (Patel, 2023). The International Society for Technology in Education (ISTE, 2023), describe how AI technology can improve learning outcomes through learning planning simulations and case analysis. This complements our findings, which show that AI-assisted learning improves prospective teachers' ability to effectively implement and validate mathematics lesson designs. Furthermore, collaboration among prospective teachers and practical experience in developing AI-assisted teaching materials, as noted by references (ISTE, 2023); (van der Meijden & Veenman, 2023), are also confirmed in our research, as participants reported greater collaboration and practical skill development in adaptive learning settings.

The findings referenced (van der Meijden & Veenman, 2023); (UNESCO, 2023), which emphasize the importance of motivational factors and the interaction between digital devices and pedagogical methodologies, are also supported by our research. Prospective teachers in our study highlighted the authenticity and relevance of instant feedback from AI, which encourages active engagement and improves their ability to evaluate and design innovative learning solutions. Furthermore, the challenges identified in the references (Garcia, 2023); (Kasneci, 2023); (van der Meijden & Veenman, 2023), such as the accuracy of AI responses, the tendency toward over-reliance, and ethical considerations, are reflected in our research, where some participants noted challenges in verifying AI answers and the risk of dependence that reduces critical thinking.

Although the reference (Rudolph, 2023) highlights potential shortcomings such as a decline in critical thinking skills due to over-reliance on AI, our results did not identify this as a significant obstacle. Instead, prospective teachers consistently viewed AI technology as a useful thinking partner in their learning process. This difference may indicate that instructional designs that emphasize critical verification and evaluation of AI outputs, as noted by the reference (UNESCO, 2021), mitigate these challenges and enhance the effectiveness

of the tool as a learning support rather than a substitute.

Overall, our research contributes to the growing body of evidence supporting the integration of generative AI in teacher education, reaffirming its transformative potential in enhancing TPACK (Mishra & Koehler, 2006) and statistical literacy Mishra (Gal, 2020). However, as with previous studies, this highlights the need for structured implementation, clear ethical guidelines, and ongoing training for educators to maximize the benefits of this technology. These findings offer practical insights for improving teacher education practices and policies, bridging the gap between pedagogical theory and real-world application through AI-based adaptive learning.

IV. CONCLUSION

This study faces several limitations that may affect the generalization of its findings. The small sample size may limit the breadth of conclusions, and participants' varying levels of familiarity with AI such as ChatGPT may have influenced their perceptions and performance, thereby introducing bias. The availability and stability of AI platforms also vary, which may potentially affect the results. Furthermore, the short duration of exposure to the technology limited the ability to assess its long-term impact on TPACK development and classroom teaching practices. Future research should expand the sample size, involve a diverse range of participants, and offer preliminary training on prompt engineering and AI literacy to minimize bias. Longitudinal studies are recommended to explore the sustained effects of AI use on teaching efficacy, and comparative studies between different AI models need to be explored for wider application. To address these issues, a plan is proposed that includes mandatory initial training on AI literacy, partnerships with educational technology platform providers, teacher workshops to integrate AI into lesson plans, and investment in digital infrastructure, with the aim of ensuring the fair and effective adoption of AI technology in teacher education.

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