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The Analysis of Pre-Service Teachers' Ability in Integrating Artificial Intelligence Technological Pedagogical Content Knowledge to Learning Instruction

Novi Ratna Dewi[1]*, Litasari Aldila Aribowo[1], Septiko Aji[1], Ayu Rahayu[1], Prasetyo Listiaji[2]

[1]Science education, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Semarang, Indonesia
[2]Doctoral School of Education, University of Szeged, Szeged, Hungary

*Corresponding author's email: noviratnadewi@mail.unnes.ac.id

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Abstract. The rapid advancement of digital technology, particularly artificial intelligence (AI), has reshaped teacher education by requiring the integration of technological, pedagogical, and content knowledge in instructional design. The AI-TPACK (artificial intelligence–technological pedagogical content knowledge) framework offers a structured foundation to support such integration in science education. This study aims to analyze the effectiveness of AI-TPACK-based learning in strengthening pre-service science teachers' competencies in designing innovative lesson plans. A quantitative approach with a pre-experimental one-group pretest–posttest design was implemented with three class group of undergraduate science education students at Universitas Negeri Semarang. The intervention addressed seven dimensions: content knowledge, pedagogical knowledge, AI technological knowledge, pedagogical content knowledge, AI technological content knowledge, AI technological pedagogical knowledge, and integrated AI-TPACK. Data were collected through a validated rubric and analyzed using descriptive statistics, gain scores, and paired comparison tests. The results of the study indicate a significant improvement in integration skills across all dimensions, with the greatest achievement in the integration of AI technological knowledge and pedagogical content knowledge within the students lesson plans. Consistent progress across class groups confirms the effectiveness of the AI-TPACK-based model in enhancing technological proficiency and meaningful pedagogy–content integration. The study concludes that systematic adoption of AI-TPACK in teacher education can improve professional readiness, nurture critical, creative, and collaborative skills, and contribute to Sustainable Development Goal 4 on quality education.
Keywords: AI-TPACK, science education, pre-service teachers, artificial intelligence integration, instructional design.

Introduction

Digital technology development has reached a big step in human life, especially the use of artificial intelligence (AI) in every sector of life, including education. In order to survive this era of globalization, education has become an important rule to prepare people for a future in which not only are they able to receive global information but also have the ability to adapt to technological development. This phenomenon has led to new breakthroughs in education, especially for the pre-service teachers, to a situation that demands them to not only master technology, but also be able to understand and be critical in a pedagogical way about how AI can be integrated into learning design (Searson et al., 2024). Previous studies have shown that intelligent education literacy among pre-service teachers still needs to be improved in order to meet the demands of the AI-based learning era (Mo & Yu, 2024).

The use of technology has caused another demand for pre-service teachers to have a better understanding of AI literacy abilities. AI literacy abilities are needed by pre-service teachers in their future so that they can design learning Instructions that are contextual, ethical, and adaptable (Guan et al., 2025; Özüdoğru & Durak, 2025; Pei et al., 2025). Science is a major that is highly relevant to data, logic, and technology exploration. In this context, technology integration like AI becomes more important, specifically for the pre-service teacher. AI quality and its relation to education programs are two important factors that affect the use of technology for pre-service teachers (Guan et al., 2025; Runge et al., 2025).

A study conducted by Irwandani et al. (2024) showed that pre-service teachers have not yet optimized their understanding of integrating technology in the science context, specifically in active learning. Pre-serviced teachers need to be trained to excel not only in using AI, but also in understanding the potential, the limitations, and the implications for sociocultural and learning processes. AI integration in the learning process not only turns the teachers into technology experts but also combines pedagogical knowledge and content knowledge in the context of technology, which is known as technological pedagogical content knowledge (TPACK). Technology optimization to support students' understanding in a particular subject is known as TPACK (Dewi et al., 2021; Jiménez Sierra et al., 2023; Su, 2023; Zeng et al., 2022). The TPACK approach has been approved as an effective framework to help educators in designing learning Instruction that integrates with technology. In the more modern context, the use of AI can expand the range of TPACK to become AI-TPACK (Celik, 2023)

In the AI era, this framework has evolved into AI-TPACK, which emphasizes the importance of teachers' knowledge of AI applications, technology-based pedagogy, and integrated content mastery (Hava & Babayiğit, 2025). Innovative and technology-based science learning has become a primary necessity in supporting the achievement of the sustainable development goals (SDGs), particularly in the area of quality education (SDG 4) (Ainiyah Ekowati et al., 2024; Purnamasari & Hanifah, 2021). The AI-TPACK framework provides guidance for pre-service teachers in designing AI-based learning that supports the achievement of SDG goals such as quality education (SDG 4). The AI-TPACK framework itself consists of seven core dimensions: content knowledge (CK), pedagogical knowledge (PK), AI technological knowledge (AI-TK), pedagogical content knowledge (PCK), AI technological pedagogical knowledge (AI-TPK), AI technological content knowledge (AI-TCK), and the comprehensive integration of AI-TPACK (Hava & Babayiğit, 2025). A study conducted by Bahtiar et al. (2023) found that systematic professional development based on AI-TPACK has a significant impact on teachers' readiness to design science instruction that is both technologically and pedagogically relevant. His finding is reinforced by Wu et al. (2025), who revealed that structured training with hands-on practice can enhance technological skills, understanding of the pedagogical applications of AI, and ethical awareness in its use.

Therefore, it is important to evaluate the extent to which pre-service science teachers are able to integrate AI through the instructional materials they design. Although several studies have discussed teachers' readiness for AI, there is still a limited number of studies that specifically examine the learning designs they create. Thus, this study aims to analyze the effectiveness of AI-TPACK integration in enhancing pre-service teachers' ability to design innovative lesson plans.

Methods

This study employed a quantitative approach with a pre-experimental design, specifically the one-group pretest–posttest design. This design was chosen because it allows researchers to evaluate changes in students' abilities before and after the treatment without involving a control group. In this context, the treatment refers to the implementation of AI-TPACK-based learning in the *science learning strategy and design* course. The subjects of this study were students from the Science Education program at Universitas Negeri Semarang (UNNES) enrolled in the odd semester, consisting of three classes (learning groups).

The research procedure began with administering a pretest to measure students' initial ability to design innovative learning based on AI-TPACK. Afterward, students participated in lectures designed using an AI-integrated approach, in which they were trained to understand and apply the seven dimensions of AI-TPACK, namely: CK, PK, AI-TK, PCK, AI-TCK, AI-TPK, and overall AI-TPACK. Once the learning process was completed, a posttest was conducted to determine the development or improvement in students' abilities.

Data collection was carried out using assessment sheets that measured the extent to which students were able to integrate each dimension of AI-TPACK into their lesson designs. Each dimension was assessed based on previously developed and validated indicators. The collected data were analyzed using a quantitative descriptive approach to describe students' ability profiles before and after the treatment. Furthermore, the N-Gain was calculated to determine the level of improvement in students' abilities, using the formula:

$$N\ gain = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}} \qquad (1)$$

Explanation:
N gain = Improvement of pre-serviced teacher ability
S_{pre} = Pre-test score
S_{post} = Post-test score
S_{max} = Maximum score

Table 1. The level of pre-service teacher ability

Score	Criteria
$0.7 \leq g \leq 1$	High
0.3 – 0.7	Moderate
$0 < g < 0.3$	Low

In addition to descriptive analysis and *N-Gain* calculation, inferential statistical analysis using the *paired sample t-test* was conducted to examine the significance of differences between pretest and posttest scores. This test was selected because it is suitable for paired data from the same subjects before and after treatment, thereby providing a more accurate measure of the effectiveness of AI-TPACK-based learning.

Results and Discussion

This study employed a one-group pretest-posttest design to analyze students' ability to integrate AI into science learning based on the TPACK model. The assessment instrument covered seven dimensions of AI-TPACK, with the results presented in Figure 1.

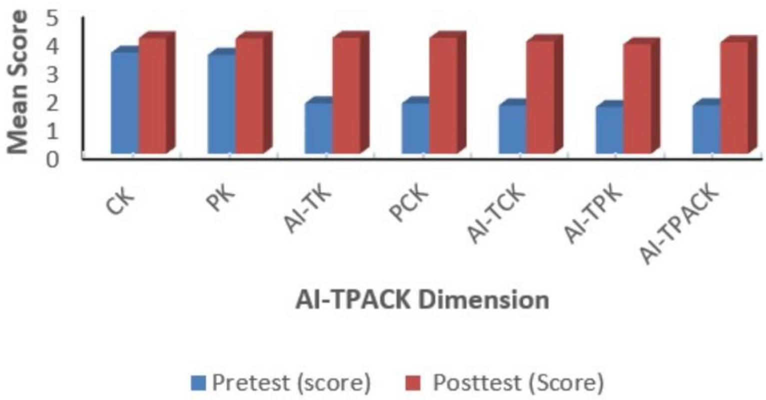

Figure 1. Comparison of pretest and posttest scores for each AI-TPACK dimension

Based on the diagram in Figure 1, the AI-TK and PCK dimensions showed the largest increases, each by +2.31 points. The AI-TCK, AI-TPK, and AI-TPACK dimensions also demonstrated significant improvements of more than 2 points. The dominant increase in the technology-related dimensions indicates the success of this learning approach in equipping students with the skills to identify, select, and use AI applications to support science learning. These findings support Celik (2023), who emphasized that Intelligent-TPACK broadens teachers' competencies by incorporating elements of AI literacy in an ethical and professional manner into lesson design.

The CK and PK dimensions also increased, although not as much as the technology-related dimensions, since students already possessed basic pedagogical and content knowledge before the intervention. Nevertheless, the integration of AI technology further enriched their ability to design more contextual and innovative learning experiences. This aligns with Dewi et al. (2022), who demonstrated that the project-based scaffolding TPACK model can significantly enhance pre-service science teachers' learning design capabilities.

From a global perspective, the findings of this study are consistent with Hava & Babayiğit (2025) and Oved & Alt (2025), who found that AI-TPACK competence is closely related to teachers' digital proficiency and identified TPACK as a key predictor of teachers' readiness to adopt AI tools for pedagogical purposes. Thus, the success of students in integrating AI into science learning materials indicates that this approach is relevant for building pre-service teachers' professional readiness in the era of artificial intelligence.

Overall, the results indicate that the implementation of AI-TPACK-based learning successfully improved pre-service science teachers' abilities in a comprehensive manner. The improvements in technology-related dimensions (AI-TK, AI-TCK, AI-TPK, and AI-TPACK) highlight the students' success in learning to use AI technology and integrating it with relevant content and pedagogical strategies. The consistent improvement across all class groups serves as an indicator that the applied learning design was effective in providing equal learning opportunities regardless of students' initial abilities. This uniformity of results is important to ensure equitable graduate quality, as mandated by SDG 4 (quality education) and reinforced by Purnamasari & Hanifah (2021), who emphasized the importance of integrating education for sustainable development (ESD) into science learning.

Table 2. Summary of normality test, paired sample t-test, and average n-gain per class

Class	Sig. Pretest	Sig. Posttest	Normality	t-value	Sig. (2-tailed)	t-Test Result	Average N-Gain	N-Gain Category
A	0.140	0.176	Normal	-13.537	0.0	Significant	0.59	Medium
B	0.958	0.703	Normal	-9.458	0.0	Significant	0.44	Medium
C	0.911	0.123	Normal	-8.732	0.0	Significant	0.38	Medium

Based on the results of the Shapiro–Wilk normality test, all class groups (A, B, and C) obtained significance values greater than 0.05 for both the pretest and posttest, indicating that the data were normally distributed. The paired sample t-test results showed that all class groups had a Sig. (2-tailed) value of 0.000 (< 0.05) with large t-count values (A = -13.537; B = -9.458; C = -8.732), indicating a consistent improvement after the treatment. The average N-Gain scores placed all class groups in the medium category, with class A achieving the highest improvement (0.59), followed by class B (0.44) and class C (0.38). The highest result in class A may be attributed to better digital literacy, effective group collaboration, and active engagement in exploring AI applications to support the development of science teaching materials. Although the average N-Gain varied between groups, all remained in the same category (medium), indicating a relatively uniform improvement in abilities.

These findings align with Celik (2023) and Dewi et al. (2022), who emphasized that AI integration ability is influenced by technological readiness, pedagogical understanding, and TPACK-based training. Hava & Babayiğit (2025) further highlighted the importance of authentic technology integration in preparing teachers for 21st-century challenges. Feldman-Maggor et al. (2025) showed that collaborative work in technology-based contexts fosters creativity and innovation. Goldman et al. (2024) and Feldman-Maggor et al. (2025) also confirmed that AI use supports cognitive achievements and develops higher-order thinking skills such as problem-solving and critical thinking.

Thus, AI-TPACK-based learning in this study contributed to increased academic scores and fostered students' critical, creative, and collaborative thinking skills. This is relevant to the achievement of SDG 4 (quality education), which emphasizes inclusive and equitable learning and the promotion of lifelong learning opportunities. This integration demonstrates that AI-TPACK can be a strategic tool in preparing pre-service science teachers to face educational challenges in the digital and artificial intelligence era. The AI-TPACK model combines CK, PK, and TK with an emphasis on AI-based technology, enabling students to not only understand content and pedagogy but also select and utilize AI technologies relevant to the learning context (Celik, 2023; Xu et al., 2025).

The significant improvement in posttest scores shows that students understand AI-TPACK concepts theoretically and can also apply them in designing science teaching materials that support SDG 4 (quality education). This is crucial in addressing the demands of 21st-century education, which requires teachers to integrate technology creatively and ethically to create quality, relevant, and inclusive learning. The analysis shows that all class groups experienced significant improvement after receiving the same AI-TPACK-based instruction. The identical Sig. (2-tailed) values (< 0.05) across all groups confirm that the improvement occurred in all students, not just in a single group. Although the N-Gain values varied slightly, the consistent category (medium) indicates that the implemented learning model provided equal opportunities for all students to enhance their ability to design teaching materials. This uniform improvement strengthens the effectiveness of the learning design, where each class group received the same materials, methods, and media, ensuring equity in learning outcomes (Sun et al., 2023).

The AI-TPACK approach proved effective not only in one class but also in delivering significant impacts across three different class groups, regardless of students' initial ability levels. The complex AI-TPACK dimensions were successfully facilitated through integrated learning, enabling students to understand AI's role in education, design technology-based teaching materials, and harmoniously integrate content, pedagogy, and technology. These results reinforce the views of Yang et al. (2025) and Wu et al. (2025) that AI-TPACK is not merely a theoretical framework but a practical instrument for preparing pre-service teachers to meet the demands of 21st-century teaching and the AI era.

The correlation between this study's findings and recent literature is further strengthened by Bautista et al. (2024), who emphasized that pre-service teachers' readiness to integrate AI is strongly influenced by hands-on experience using AI-based tools. Cheng et al. (2025) found that extending the TPACK framework with AI components can more accurately predict AI-based teaching readiness. Karataş & Ataç (2025) discovered that the relationship between AI-TPACK components is mutually reinforcing, where improvements in AI-TK significantly boost overall AI-TPACK.

Furthermore, Alwakid et al. (2025) highlighted that mastery of AI-TPACK not only affects the quality of instructional planning but also directly impacts student learning performance within an outcome-based education framework. Dogan et al. (2025) stressed that AI-based teacher professional development should be designed with an explicit TPACK approach, while Lakhe Shrestha et al. (2025) showed that generative AI skills within the TPACK framework can drive adaptive instructional design innovation. Nguyen et al. (2025) added that the successful implementation of AI-TPACK requires strategies to address initial resistance and infrastructure limitations.

Conclusion

The research findings indicate that the integration of AI-TPACK effectively enhances pre-service science teachers' competencies in designing innovative lesson plans. Competencies in integrating all dimensions of AI-TPACK showed improvement. The highest improvement was seen in the competencies of integrating AI-TK and PCK, supported by N-Gain results in the medium category and significant differences between pretest and posttest scores. These results confirm that AI-TPACK-based learning strengthens the ability of pre-service teachers to design innovative lesson plans and supports their academic achievement, critical thinking, creativity, and collaboration skills. Therefore, systematic integration of AI-TPACK in science education is essential to prepare graduates for the demands of 21st-century learning and the responsible use of artificial intelligence.

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