

# AI-TPACK enhanced project-based STEM pedagogy: A model for cultivating 21st century skills in pre-service teachers

*Ali Fakhruddin*<sup>1\*</sup>, *Monica Widyaswari*<sup>2</sup> and *Adjie Pradana Wibowo*<sup>3</sup>

<sup>1</sup>Elementary Teacher Education, Faculty of Education, Universitas Negeri Surabaya, Indonesia

<sup>2</sup>Non-Formal Education, Faculty of Education, Universitas Negeri Surabaya, Indonesia

<sup>3</sup>Master of Education in Digital Learning, Monash University, Australia

**Abstract.** The objective of this paper is to evaluate the performance of the AI-TPACK-lived project-based STEM pedagogy model for the improvement of the 21st-century skills of the students of teacher education. The idea is perfectly in line with Technological Pedagogical Content Knowledge (TPACK), AI, project-based learning (PjBL), and also a cross-disciplinary STEM approach to provide an adaptable and contextual learning environment. The methods of quantitative, qualitative, and one-group pretest-posttest were used for a study. It covered 213 potential teacher students. The Partnership for 21st Century Learning (P21) Framework-based 21st-century skills scale determined the level of critical thinking, creativity, communication, and cooperation. The paired sample t-test and Cohen's d calculation were used to determine the intervention's significance and efficacy. Besides, in order to learn about students' experiences throughout the learning process, semi-structured interviews were conducted. The authors state that their work is consistent with this model of students' critical thinking, creativity, communication, and collaboration skills. The qualitative data are in agreement with the student stories about the involvement, the self-reflection, and the collaborative nature of the learning experience as well. The work promotes the utilization of the AI-TPACK model in teacher education as an innovative pedagogical strategy that can effectively respond to 21st-century challenges.

## 1 Introduction

Digital revolution reformed education, giving paradigms a new shape, and in turn, humbler socios needed to learn all that, plus pedagogic, cognitive skills of higher order, collaboration, creativity, and tech integration [1,2]. The Technological Pedagogical Content Knowledge (TPACK) framework highlights the significance of the balance among the educational process, which includes subject knowledge, pedagogical techniques, and technological integration. AI rapidly developed technology now offers the possibility of AI integration in the TPACK framework that has the power capacity for adaptive, personalized, and data-driven learning environments [3,4].

---

\* Corresponding author: [alifakhruddin@unesa.ac.id](mailto:alifakhruddin@unesa.ac.id)

Meanwhile, a project-based learning approach (PjBL) represents a constructivist strategy placing primary emphasis on the students' active participation in the solving of authentic problems, switching of collaborative work, and the use of multiple sources of learning [5,6]. PjBL in association with STEM education, this approach gains force in driving the infusion across the various disciplines and in forming the bridges between the theory and the daily life practice [7-10].

The utilization of AI, TPACK, PjBL, and STEM in a unified pedagogical model is a new way for teacher education of 21st-century student learning needs. The model highlights not only the content knowledge and the basic skills but also the witty use of AI that will improve the learning effectiveness. Yet to be fully explored and tapped in Southeast Asian regions, this approach remains. AI helps in personalizing learning, managing the data, and providing immediate feedback [11]. Nevertheless, it also calls for educators to be prepared, both in technical and ethical understanding [12,13]. So it is indeed important to make sure that the next generation of teachers is equipped not only with technological know-how but also with a social and moral understanding of AI when they impart primary and secondary education.

Many global research studies highlighted the importance of teaching 21st-century skills to prospective teachers [14,15]. The Partnership for 21st Century Skills (P21) provides 21st-century skills in the form of such areas as learning and innovation (critical thinking, creativity, communication, and collaboration); information, media, and technology; and life and career. Therefore, the acquisition of these skills involves a learning approach that requires students to be more active and reflect more instead of using traditional ways.

It has been demonstrated in prior studies that the implementation of the PjBL-STEM method improves students' problem-solving skills and their technological literacy [16,17]. Meanwhile, a survey of the integration of TPACK in teacher education also shows that TPACK-based training can enhance the quality of planning and implementation of learning by prospective teachers [18,19]. However, limited research has examined how these two frameworks can be combined with AI to address the demands of 21st-century education, particularly in the Indonesian context.

This study explores the impact of the AI-TPACK project-based STEM model on the development of 21st-century competencies among Indonesian pre-service teachers. Employing a quantitative methodology, the research assesses the model's effectiveness in enhancing students' technological literacy, collaboration, critical thinking, and instructional design skills. Theoretically, this study contributes for ongoing discourse on the role of AI in constructivist and technology-enhanced pedagogies. Practically, it offers a scalable framework applicable to teacher education programs, policy development, and curriculum design in response to the demands of the digital era.

## **2 Method**

This quantitative study reveals that the AI-TPACK project-based STEM education paradigm has a significant impact on prospective teachers' 21st-century abilities. It comprised of 213 Indonesian public university fifth-semester students. They were selected through purposive sampling based on similar academic backgrounds and STEM learning experience. The main instrument was a 21st-century skills questionnaire based on the P21 Framework, covering five dimensions: critical thinking, creativity, communication, collaboration, and technology literacy, with items rated on a 5-point Likert scale. Content validity was ensured through expert judgment, and reliability testing yielded  $\alpha = 0.89$ . Data from a paired sample t-test ( $p < 0.05$ ) and Cohen's D were used for the effect size estimation. Qualitative data from semi-structured interviews were transcribed and thematically analyzed to capture students' perceptions and experiences with the AI-TPACK learning model.

### 3 Results

#### 3.1 The contribution of AI integration in the PjBL-STEM learning model to 21st-century skills development

The paired sample t-test was carried out to find out the significant dissimilarities between the pretest and posttest performance of the teacher students who undertook an AI-integrated STEM project-based learning initiative. An investigation to assess the impact of employing interventions in 21st-century skills was conducted. The statistical analysis results are depicted.

**Table 1.** Results of the 2nd Century Skill Scale Dependent Group T-Test.

		<i>N</i>	<i>X</i>	<i>ss</i>	<i>Sd</i>	<i>t</i>	<i>p</i>
21st-Century Skills Scale	Pre-test	213	2.914	.182	34	-17.54	.00
	Post-test	213	3.783	.282			

Table 1 depicts that students' pre-test scores ( $M = 2.914$ ,  $SD = 0.182$ ) and post-test scores ( $M = 3.783$ ,  $SD = 0.282$ ) differ drastically in favor of post-test results [ $t(34) = -17.54$ ,  $p = 0.00$ ]. Such results confirm that completing STEM tasks driven by AI skills enhances students' skills in the 21st century in order to find the difference among the five dimensions of the 21st-century skills scale, a dependent samples t-test was carried out. The results for the different dimensions are laid out below in a separate table.

**Table 2.** The Results of the Dependent Group T-Test Are Related to Critical Thinking.

		<i>N</i>	<i>X</i>	<i>ss</i>	<i>Sd</i>	<i>t</i>	<i>p</i>
Critical Thinking Skills	Pre-Test	213	3.126	.341	34	-14.17	.00
	Post-Test	213	3.862	.218			

The pre-test score ( $X = 3.126$ ,  $S = 0.341$ ) was definitely not the same as the post-test score ( $X = 3.862$ ,  $S = 0.218$ ), which revealed a positive post-test result [ $t(34) = -14.17$ ,  $p = 0.00$ ]. The data indicates that STEM project-based learning with AI is one of the methods to promote students' critical thinking. The outcomes of the dependent group t-test for creative thinking skills, another element of the scale, are laid out in the interpretation of Table 3.

**Table 3.** The Results of the Dependent Group T-Test Are Related to Creative Thinking.

		<i>N</i>	<i>X</i>	<i>ss</i>	<i>Sd</i>	<i>t</i>	<i>p</i>
Creative Skills	Pre-Test	213	2.031	.288	34	-19.88	.00
	Post-Test	213	4.124	.433			

Table 3 exemplifies that the post-test score was significantly greater than the pre-test score ( $X = 2.031$ ,  $S = 0.288$ ) [ $t(34) = -19.88$ ,  $p = 0.00$ ]. Following this, students' critical thinking and problem-solving abilities are being improved by the utilization of STEM project-based learning incorporating AI. Table 4 exhibits the dependent group's t-test for the variable of communication skills.

**Table 4.** The Results of The Dependent Group T-Test Are Related to Communication.

		<i>N</i>	<i>X</i>	<i>ss</i>	<i>Sd</i>	<i>t</i>	<i>p</i>
Communication Skills	Pre-Test	213	2.811	.272	34	-10.13	.00
	Post-Test	213	3.805	.291			

Pre-test score ( $X = 2.811$ ,  $S = 0.271$ ) was far below post-test score [ $t(34) = -10.13$ ,  $p = 0.00$ ]. The findings are consistent with the idea that STEM project-based learning aided by AI leads to the enhancement of students' skills and creativity.

The dependent group t-test results for cooperation abilities, a dimension of the scale, are presented in Table 5.

**Table 5.** The Results of the Dependent Group T-Test Are Related to Collaboration.

		<i>N</i>	<i>X</i>	<i>ss</i>	<i>Sd</i>	<i>t</i>	<i>p</i>
Communication	Pre-Test	213	3.271	.285	34	-3.72	.002
Skills	Post-Test	213	3.641	.512			

From Table 5, we can see a significant difference statistically between the pre-test score ( $X = 3.271$ ,  $S = 0.285$ ) and the post-test score ( $X = 3.512$ ,  $S = 0.512$ ), favoring the post-test. [ $t(34) = -3.72$ ,  $p = 0.002$ ]. The data are conclusive that AI in STEM project-based learning positively affects students' teamwork skills. Project-based STEM learning with AI facilitates 21st-century skills such as critical thinking, creativity, communication, and collaboration.

### 3.2 Student Experience in Learning AI-Based STEM Projects

This section presents qualitative findings obtained through semi-structured interviews with students. The data were analyzed to identify themes, categories, and codes that reflected participants' experiences in STEM learning activities. The analytical results are systematically provided in Table 6.

**Table 6.** Thematic coding of students' 21st century skills in learning AI-Based STEM projects.

Theme	Category	Code	Student Responses
21st-Century Skills	Critical Thinking	Problem-solving in projects	"We discussed several solutions before choosing the best one to test using AI."
	Creativity	Innovative design ideas	"We created new ways to improve our model, like integrating VR for engagement."
	Communication	Peer dialogue and feedback	"Giving and receiving feedback improved our understanding and project quality."
	Collaboration	Teamwork	"Working together helped us complete tasks faster and include everyone's ideas."

AI bestows pre-service teachers' 21st-century capabilities, are more in critical thinking, creativity, communication, and teamwork in STEM project-based learning. AI technology positively influences problem-solving, creativity, peer involvement, and collaboration, which in turn makes learning more exciting and student-tuned. It also leads to higher cognitive and job readiness.

## 4 Discussion

### 4.1 Cultivating critical thinking through project-based STEM learning integrated with AI

Critical thinking is a fundamental 21st-century skill beyond necessary for pre-service teachers who deal with solving the complicated, interdisciplinary challenges of modern education. It means breaking down, judging, mixing up the work, and making choices, which should be based on evidence. The AI-TPACK STEM model enables critical thinking through going on a real-world challenge and getting support from AI instruments, such as the visualization of data, simulations, and the provision of feedback in real-time. These technologies facilitate more profound investigation, the assessment of the data, and the

creation of alternative solutions. This method also highlights the repetitive reflection, whereby students check if their assumptions are right, change their ideas, and have collaborative discussions. AI additionally facilitates this process by providing instant feedback and visual comparisons, enabling students to exercise their analytical thinking and build a shared understanding.

In conclusion, this integration not only enhances critical thinking but also strengthens communication, collaboration, and creativity—essential competencies for preparing future educators to adapt effectively and innovate within the fast-changing educational landscape. These results align with existing literature on the potential of project-based, reflective, and problem-oriented learning approaches to cultivate higher-order thinking, particularly when reinforced by digital technologies [20]. In the meantime, AI-based learning has been found to be very effective by several studies, only in a few instances, to enhance critical thinking skills, through data-driven problem-solving, and visualization of thought processes, which make learners more aware of the cognitive steps they take [21,22].

## **4.2 Creativity as an expression of innovation in technology-based learning**

Creativity is a core competency in 21st-century education, essential for preparing adaptive and innovative prospective teachers. In teacher education, creativity involves not only generating ideas but also experimenting, thinking critically, and solving real-world problems in relevant and applicable ways. In AI-TPACK-enhanced Project-Based STEM learning, creativity is fostered through collaborative, technology-supported design. Students integrate STEM content with design thinking and basic coding to create innovative learning media. AI tools—such as feedback systems and real-time suggestions—enable iterative refinement. Group discussions and peer input, supported by AI insights, further enhance practical and original ideas in educational product development.

These findings are consistent with prior research, which shows that open-ended, technology-supported tasks enhance creativity in education and that AI integration expands design possibilities in STEM learning. Interactive technologies have been found to improve creative output among teacher candidates [23], increase design flexibility [24], and boost creative exploration and intrinsic motivation. Thus, integrating AI into project-based STEM learning nurtures not only the creation of innovative outcomes but also an innovative mindset characterized by experimentation, resilience, and the ability to link diverse concepts. For future educators, this is essential for designing timely, relevant, and context-aware learning experiences suited to the demands of the information age.

## **4.3 Communication as a collaborative competency in AI-STEM learning**

Communication is a key in 21st-century competency that plays a vital role in fostering collaboration and reflective learning within teacher education. It encompasses more than the mere exchange of information. It involves active listening, empathetic responding, negotiating meaning, and constructing coherent arguments core elements that define effective and professional teaching practice. In the AI-TPACK integrated Project-Based STEM model, communication is central to teamwork, requiring students to coordinate roles, express ideas, and engage in dialogue. AI supports this by offering digital tools such as discussion platforms, interactive media, and automated feedback that enable structured, persuasive, multimodal communication. It also helps students refine arguments and communicate with greater precision, while group dynamics foster communication through active dialogue and mutual respect. These experiences not only build an academic setting where future teachers learn to communicate across diverse perspectives but also promote such cultures.

These findings are supported by survey data indicating that project-based learning greatly enhances learners' communication skills by requiring active involvement in negotiation, discussion, and presentation during collaborative tasks. The inherently social nature of cooperative learning contributes significantly to the development of both communication abilities and conceptual understanding [25]. Furthermore, collaborative technology and AI suggest that these tools serve as catalysts for fostering more reflective, evidence-based, and dynamic communication within team-based learning environments [26,27]. In AI-TPACK-based STEM learning, communication serves not just as information exchange but as a strategic skill that promotes collaboration and creativity. For preservice teachers, proficiency in academic and professional communication is crucial for developing inclusive, dialogic, and data-driven teaching practices, key to navigate today's complex, digitally connected education systems.

#### **4.4 Collaboration as the core of AI-TPACK project-based learning**

Collaboration is undoubtedly the most important competency in Project-Based Learning. Moreover, its importance is emphasized in the case of pre-service teachers, here are the people who must work together in different roles, make joint decisions, and take responsibility for the work performed together. In this model, collaboration gets even more powerful since the digital tools make it easier to communicate and find solutions to the problems that teams face in real-world situations. AI facilitates teamwork on Learning Management System (LMS) platforms, cloud tools, and contribution trackers, thus allowing task division, progress monitoring, and equitable participation. Students have expressed that these functionalities have helped them to be more responsible and better coordinate the group. The model promotes cross-disciplinary collaboration, where students merge their expertise from the fields of pedagogy, technology, and design to come up with educational solutions that are innovative. AI facilitates the process of bringing various perspectives together and being the dispenser of feedback, providing a better understanding of group interaction. Hence, the student asks for skills such as interpersonal skills, the development of conflict resolution skills, and the cultivation of a collaborative mindset that mimics real-world teaching practices through this process. AI also does this by studying team dynamics and creating situations of inclusive and transparent collaboration.

Research supports that the integration of PjBL with the AI-TPACK framework has proven effective in promoting green awareness, social responsibility, and data-driven decision-making [28,29]. This approach not only cultivates essential social skills but also fosters cross-disciplinary competencies critical qualities for future educators aiming to create inclusive and adaptable learning environments.

#### **4.5 Transforming learning attitudes and environments through the AI-TPACK enhanced project-based STEM learning model**

The AI-TPACK supplemented project-based STEM learning framework goes beyond the cognitive faculties of students and positively influences their attitude and the classroom environment. It supports the concept of technology acceptance, self-reflective learning, and the courage of students, along with co-operative work that is the essence of the 21st-century educator's personality. The learners are no longer the passive users of technology but instead the active agents who design their learning journeys, harnessing AI for the whole process of planning, implementation, and receiving feedback. The learning turns more individual, interactive, and significant if AI comes in as a helper. As a result, learning shifts toward a student-driven environment centered on dialogue and real-world problem-solving. The change is not only technological but also pedagogical. It affects how students think, learn,

and communicate with each other. It requires the whole teacher training system to be innovative: teachers getting better at digital skills, coming up with projects that incorporate different subjects, and evaluations that reflect the new skills.

While teacher education remains in a state of flux as it attempts to catch up with fast technological and pedagogical changes, stages like AI-TPACK-advanced project-based STEM learning present a definite course to future-oriented teaching. This model prepares the pre-service teachers for the 21st-century competencies, and it makes them to develop the habit of perpetual learning, being innovative, and engaging with ethical issues concerning technology. In future, further investigations and organizational backing are very important for this model to be widely adopted, to improve its format, and to make sure it can fit into different educational situations.

## 5 Conclusion

The AI-TPACK Enhanced Project-Based STEM Pedagogy model certainly demonstrates very strong results in good thinking, creativity, communication, and cooperation among preservice teachers. The model implements AI in the TPACK framework within the STEM project outlines, thus enabling the learning to be more alive, expressive, and co-operative. AI serves as a tool that empowers instructional design, feedback, and teamwork. This model is an appropriate and scalable strategy for modern teacher education, which is also consistent with the requirements of 21st-century classrooms. The authors sincerely thank the preservice teachers for their valuable participation and acknowledge the support received during AI integration, which was vital to developing the AI-TPACK enhanced Project-Based STEM model.

## References

1. D. O. Göksün and A. Kurt, *Educ. Sci.* **42**, 190 (2017)
2. K. Agustini, I. W. Santyasa, and N. M. Ratminingsih, *J. Phys.: Conf. Ser.* **1387**, 012035 (2019)
3. E. Baran and E. Uygun, *Australas. J. Educ. Technol.* **32**, 47 (2016)
4. H. Abubakir and Y. Alshaboul, *Heliyon* **9**, e17348 (2023)
5. Asman, M. Kumaro, and M. S. Barliana, in *Proc. Int. Conf. Innovation Eng. Voc. Educ. (ICIEVE)*, Atlantis Press, 88 (2022).
6. A. Hariyadi, Dumiyati, Tukiyo, and A. Darmuki, *Int. J. Instr.* **16**, 3 (2023)
7. A. Mustadi, A. Ghufron, and A. Fakhrudin, *Edelweiss Appl. Sci. Technol.* **8**, 1249 (2024)
8. N. Diana, Yohannes, and Y. Sukma, *J. Phys.: Conf. Ser.* **1882**, 012146 (2021)
9. M. Baran, M. Baran, F. Karakoyun, and A. Maskan, *J. Turk. Sci. Educ.* **18**, 4 (2021)
10. R. S. Retno, P. Purnomo, A. Hidayat, and A. Mashfufah, *Asian Educ. Dev. Stud.* **14**, (2025)
11. P. Limna, S. Jakwatanatham, S. Siripattanakul, P. Kaewpuang, and P. Sriboonruang, *Advance Knowl. Exec.* **1**, 1 (2022).
12. L. Kohnke, D. Zou, A. W. Ou, and M. M. Gu, *Comput. Educ.: Artif. Intell.* **8**, 100398 (2025)

13. X. Wang, L. Li, S. C. Tan, L. Yang, and J. Lei, *Comput. Hum. Behav.* **146**, 107798 (2023)
14. A. Afandi, S. Sajidan, M. Akhyar, and N. Suryani, *J. Pendidik. IPA Indones.* **8**, 1, Art. 1 (2019)
15. H. Almazroa and W. Alotaibi, *Sustainability.* **15**, Art. 9 (2023)
16. R. Megawati, *Open Educ. Stud.* **6**, 1 (2024)
17. K. R. Dhany, D. Yulianti, and Abdurrahman, *J. Penelit. Pendidik. IPA.* **11**, 1 (2025)
18. J. H. L. Koh, C. S. Chai, and W. Y. Lim, *J. Educ. Comput. Res.* **55**, 172 (2017)
19. Á. A. Jiménez Sierra, J. M. Ortega Iglesias, J. Cabero-Almenara, and A. Palacios-Rodríguez, *Front. Educ.*, 8 (2023).
20. L. Zhang and Y. Ma, *Front. Psychol.*, 14 (2023)
21. W. Promma, N. Imjai, B. Usman, and S. Aujirapongpan, *Comput. Educ.* **8**, 100382 (2025)
22. A. M. Vieriu and G. Petrea, *Educ. Sci.* **15**, 3 (2025)
23. C.-F. Chang, N. Annisa, and K.-Z. Chen, *Educ. Inf. Technol.* **30**, 8689 (2025)
24. A. Y. Wang, *Educ. Inf. Technol.* **27**, 9935 (2022)
25. R. M. Gillies, *Aust. J. Teach. Educ.* **41**, 3 (2016)
26. K. Zhang and A. B. Aslan, *Comput. Educ.: Artif. Intell.* **2**, 100025 (2021)
27. C.-C. Tsai, C.-C. Chung, Y.-M. Cheng, and S.-J. Lou, *Front. Psychol.*, 13 (2022)
28. A. Bautista et al., *Educ. Process: Int. J.* **13**, 40 (2024)
29. S. Dogan, U. Y. Nalbantoglu, I. Celik, and N. A. Dogan, *Prof. Dev. Educ.* **51**, 519 (2025)