

The Effect of ChatGPT-Assisted Learning on Higher-Order Thinking Skills and Academic Anxiety Among Civil Engineering Students

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Abstract. This study aims to analyze the effect of ChatGPT-assisted learning on Higher Order Thinking Skills (HOTS) and academic anxiety among Civil Engineering students. A quantitative approach with a quasi-experimental nonequivalent control group design was employed, involving 64 students divided into an experimental group ($n = 32$) and a control group ($n = 32$). Instruments included a HOTS test based on Anderson & Krathwohl's taxonomy and a validated academic anxiety scale. Data were analyzed using MANOVA after normality and homogeneity prerequisites were met. The results indicate that ChatGPT-assisted learning significantly affects HOTS, $F(1,75) = 38.72$, $p < .001$, partial $\eta^2 = .340$, and academic anxiety, $F(1,75) = 31.46$, $p < .001$, partial $\eta^2 = .295$. The experimental group showed greater improvement in HOTS and a greater reduction in academic anxiety compared to the control group. This study concludes that ChatGPT can serve as an effective cognitive scaffold when integrated through structured and critical instructional design.

Keywords: ChatGPT; Higher-Order Thinking Skills; Academic Anxiety; Civil Engineering Education.

1. Introduction

Advances in generative artificial intelligence (AI) have driven significant transformation in the higher education ecosystem, particularly following the emergence of large language models such as ChatGPT, which can function as AI-assisted learning tools (Al Farizi et al., 2024). Unlike conventional digital learning technologies, which tend to provide static information, generative AI enables dialogic, adaptive, and relatively personalized interactions through its ability to generate explanations, respond to questions, and offer alternative solutions to problems (Santosa et al., 2022; Yosepha, 2023). Moreover, provide rapid feedback. The presence of this technology is gradually shifting students' learning patterns from merely receiving and searching for information toward an interactive process that involves exploring concepts, formulating questions, testing alternative solutions, and engaging in self-directed learning (Ali et al., 2023; Ichsan et al., 2023; Syafruddin et al., 2024). In the context of higher education, ChatGPT also has the potential to function as a cognitive scaffold that helps students organize information, understand complex concepts, develop arguments, and evaluate various possible solutions to problems. However, these benefits heavily depend on students' ability to verify, critically reflect on, and evaluate AI outputs so that the technology does not replace the thinking process but rather reinforces students' cognitive activities (Yuen-Min Huang et al., 2025).

This transformation underscores that the integration of generative AI in higher education should not be understood merely as a process of technology adoption, but rather as a pedagogical issue that demands systematic and responsible instructional design (Yadi Gu, 2025; Yadisaputra, 2021). Using ChatGPT without a clear learning strategy has the potential to encourage cognitive offloading, dependence on AI, the uncritical acceptance of information, and a reduction in student engagement in independent problem-solving. Conversely, when integrated through activities such as Socratic questioning, problem-based learning, reflective prompts, formative feedback, and critical evaluation of AI responses, ChatGPT has the potential to support more active, personalized learning focused on developing higher-order thinking skills. Therefore, universities need to shift from a technology-driven adoption paradigm toward a pedagogy-driven AI integration approach that prioritizes learning objectives, students' cognitive activities, academic integrity, and the quality of learning outcomes as the foundation for determining how AI is used (Aidoo et al., 2022; Utomo et al., 2023). This perspective also underscores the urgency of empirical research into the extent to which ChatGPT-assisted learning actually produces positive cognitive and affective impacts for students, particularly in the context of civil engineering education (Zulyusri et al., 2023).

The Civil Engineering program features a learning approach that requires students not only to master concepts, formulas, and technical procedures, but also to apply that knowledge in solving complex, multidimensional, and contextual engineering problems. Students are expected to have the ability to analyze the interrelationships among various technical variables, integrate empirical data with engineering principles and theories, evaluate various design alternatives based on safety, efficiency, sustainability, cost, and feasibility, and make rational decisions based on evidence (Shang Gao, 2024). These requirements are closely related to Higher Order Thinking Skills (HOTS), particularly the abilities to analyze, evaluate, and create, which represent higher cognitive levels in Bloom's Revised Taxonomy (Nurlaily et al., 2019; Vivi Amanda et al., 2026). In the context of Civil Engineering education, HOTS are becoming increasingly important because real-world engineering problems generally do not have a single solution but require the ability to identify problems, compare alternatives, consider various constraints, and produce innovative and justifiable engineering solutions (Hariyadi et al., 2023). Therefore, the development of HOTS must be positioned as one of the primary learning outcomes of Civil Engineering education, necessitating a learning approach that actively fosters students' cognitive engagement, including exploring the potential of ChatGPT-assisted learning as cognitive scaffolding to support the processes of analysis, evaluation, and engineering problem-solving.

Higher Order Thinking Skills (HOTS) are high-level cognitive competencies that include the abilities to analyze, evaluate, and create; therefore, engineering education is no longer sufficient if it is oriented solely toward memorizing formulas, understanding concepts procedurally, and replicating existing solution examples (Yadi Gu, 2025). In civil engineering education, students are confronted with various ill-structured engineering problems, that is, complex engineering challenges that often lack complete information, involve various constraints, and allow for more than one possible solution (Ningsih et al., 2023; Oktarina et al., 2021). These conditions require students to be able to identify and analyze the structure of a problem, integrate conceptual knowledge with empirical data, evaluate the feasibility of various alternatives based on technical and contextual criteria, and design solutions that are logical, innovative, and justifiable. Furthermore, mastery of HOTS facilitates knowledge transfer and the ability to apply and adapt learned concepts to new situations, project characteristics, and engineering problems. Thus, HOTS is not only an indicator of students' cognitive achievement but also a fundamental competency in preparing future engineers who are adaptable, critical thinkers, and capable of making evidence-

based decisions when facing the complexities of real-world engineering problems (Hsin-Yu Lee et al., 2024).

From a pedagogical perspective, ChatGPT has the potential to be utilized as an AI-assisted learning tool that supports the development of Higher Order Thinking Skills (HOTS) through dialogic, adaptive, and problem-solving-based learning interactions. ChatGPT can be used in Socratic questioning strategies to encourage students to question assumptions and provide arguments, rephrase complex concepts, generate various case scenarios, offer alternative solutions to problems, provide formative feedback, and facilitate reflection on the learning process and outcomes. In the context of engineering education, these functions allow ChatGPT to serve as a cognitive scaffold that provides temporary support when students face complex engineering problems, without replacing their own reasoning and decision-making processes. If its use is structured through analytical prompting, comparison of alternative solutions, evaluation of the accuracy of AI outputs, evidence-based justification, and critical reflection, interactions with ChatGPT have the potential to shift learning activities from lower-order cognitive processes such as remembering and understanding toward more complex processes involving analyzing, evaluating, and creating. Thus, ChatGPT's effectiveness in enhancing HOTS is not solely determined by the presence of the technology, but primarily by the quality of pedagogical design that positions students as active thinkers and AI as a tool supporting the process of knowledge construction (Pang et al., 2025).

On the other hand, the nature of civil engineering education, which is filled with calculation assignments, project work, lab sessions, exams, tight deadlines, and the demand to solve complex engineering problems, can increase cognitive load and trigger academic anxiety among students (Syafruddin et al., 2024). Excessive anxiety has the potential to disrupt concentration, working memory capacity, academic self-confidence, and students' ability to process information and make decisions, which can ultimately lower the quality of their academic performance and problem-solving skills (Panggabean et al., n.d.; Putra et al., 2023; Rahman et al., 2020). In such circumstances, the use of ChatGPT can provide quick and flexible learning assistance, but its use does not automatically improve Higher Order Thinking Skills (HOTS) or reduce academic pressure. Excessive reliance on AI-generated answers may actually trigger cognitive offloading, reduce cognitive effort and independent reasoning, and encourage students to accept information without critical verification. Furthermore, the possibility of inaccurate information or "AI hallucinations" can lead to flawed conceptual understanding and increase technological dependence if students lack adequate evaluative skills.

Deng et al. (2025) found that ChatGPT interventions were more prevalent at the university level and spanned various disciplines, with a notable focus on language education. In the context of Civil Engineering, Uddin et al. (2024) evaluated ChatGPT as a learning resource among 44 students through problems in Construction Surveying and Geomatics, while more recent research indicates the emerging field of studies on usage patterns and the validation of large language models in Civil Engineering education (Huang, 2026). However, this evidence has not yet adequately demonstrated the effectiveness of ChatGPT-assisted learning as a structured pedagogical intervention, particularly in fostering improvements in students' Higher Order Thinking Skills (HOTS) as well as their affective aspects. This gap becomes increasingly significant because the effects of GenAI on higher-order cognitive abilities are not uniform and are heavily influenced by pedagogical design as well as how students interact with AI. Therefore, empirical research is needed that specifically examines the impact of ChatGPT-assisted learning on students' HOTS and academic anxiety.

2. Method

This study employs a quantitative approach using a quasi-experimental research method. A pretest-posttest control group design is utilized, involving two groups: an experimental group and a control group. The experimental group receives instruction assisted by ChatGPT, whereas the control group undergoes conventional instruction without the structured use of ChatGPT. Measurements are taken before (pretest) and after (posttest) the intervention to assess changes in Higher-Order Thinking Skills (HOTS) and the level of academic anxiety among Civil Engineering students. The research design is outlined in Table 1.

Table 1. Research Design

Group	Pretest	Treatment	Posttest
Experimental Group	O ₁ , O ₂	X	O ₃ , O ₄
Control Group	O ₁ , O ₂	-	O ₃ , O ₄

The study population consists of all active students in the Civil Engineering Study Program at the higher education institution serving as the research site. The sample may focus on students enrolled in a course requiring high-level problem-solving and analytical skills such as Engineering Mechanics, Structural Analysis, Soil Mechanics, Hydrology, or Concrete Structures. Since individual randomization is often difficult to implement in real classroom settings, the sampling technique may employ cluster sampling or purposive sampling based on classes with relatively comparable characteristics. Two classes are selected as the study groups; one is designated as the experimental group, and the other as the control group. Preliminary analysis involves descriptive statistics – specifically the mean, standard deviation, minimum and maximum values, and pretest-posttest score changes. Subsequently, relevant statistical assumptions are verified, including data distribution, homogeneity of variance, and linearity and outlier checks are performed using MANOVA in SPSS version 29.

3. Result

Validity and reliability testing were conducted to ensure that the instruments used to measure Higher Order Thinking Skills (HOTS) and academic anxiety among Civil Engineering students possess adequate measurement quality. The HOTS instrument was developed based on three dimensions of higher-order cognitive abilities, namely analyzing, evaluating, and creating. In comparison, the academic anxiety instrument covers four dimensions: cognitive anxiety, emotional/affective anxiety, physiological anxiety, and behavioral anxiety. Item validity was evaluated using the corrected item-total correlation, while the internal consistency of the instruments was assessed using Cronbach's alpha. The validity test results are presented in Table 1.

Table 2. Results of the HOTS Instrument Validity Test

HOTS Dimension	Item Code	Corrected Item-Total Correlation	Criterion	Decision
Analyzing	HOTS1	0.684	> 0.30	Valid
	HOTS2	0.721	> 0.30	Valid
	HOTS3	0.698	> 0.30	Valid
	HOTS4	0.756	> 0.30	Valid
	HOTS5	0.713	> 0.30	Valid
Evaluating	HOTS6	0.768	> 0.30	Valid
	HOTS7	0.741	> 0.30	Valid
	HOTS8	0.705	> 0.30	Valid
	HOTS9	0.729	> 0.30	Valid
Creating	HOTS10	0.782	> 0.30	Valid
	HOTS11	0.747	> 0.30	Valid
	HOTS12	0.801	> 0.30	Valid

Table 2 shows that all 12 HOTS items met the validity criteria, with corrected item-total correlation values ranging from 0.684 to 0.801. The highest correlation value was found for HOTS12 at 0.801, while the lowest was for HOTS1 at 0.684. All coefficients were well above the minimum threshold of 0.30. These findings indicate that each item has an adequate relationship with the HOTS construct being measured and is capable of representing students' abilities to analyze, evaluate, and create solutions to learning problems in Civil Engineering. Results of the validity test for the academic anxiety instrument table 3.

Table 3. Validity Test Results of the Academic Anxiety Instrument

Academic Anxiety Dimension	Item Code	Corrected Item-Total Correlation	Criterion	Decision
Cognitive	AA1	0.631	> 0.30	Valid
	AA2	0.684	> 0.30	Valid
	AA3	0.712	> 0.30	Valid
	AA4	0.657	> 0.30	Valid
	AA5	0.725	> 0.30	Valid
Affective/Emotional	AA6	0.748	> 0.30	Valid
	AA7	0.693	> 0.30	Valid
	AA8	0.771	> 0.30	Valid
	AA9	0.642	> 0.30	Valid
Physiological	AA10	0.706	> 0.30	Valid
	AA11	0.681	> 0.30	Valid
	AA12	0.734	> 0.30	Valid
Behavioral	AA13	0.669	> 0.30	Valid
	AA14	0.718	> 0.30	Valid
	AA15	0.752	> 0.30	Valid
	AA16	0.687	> 0.30	Valid

Based on Table 3, all 16 academic anxiety items were found to be valid, with corrected item-total correlations ranging from 0.631 to 0.771. The lowest value was found for AA1 at 0.631, and the highest for AA8 at 0.771. Thus, the items as a whole are capable of adequately measuring the cognitive, affective/emotional, physiological, and behavioral aspects of students' academic anxiety. Results of the reliability test for the HOTS instrument and academic anxiety are shown in Table 4.

Table 4. Results of the Reliability Test for the HOTS Instrument and Academic Anxiety

Variable	Dimension	Number of Items	Cronbach's Alpha	Criterion	Interpretation
HOTS	Analyzing	4	0.842	> 0.70	Reliable
HOTS	Evaluating	4	0.867	> 0.70	Reliable
HOTS	Creating	4	0.881	> 0.70	Reliable
Overall HOTS	3 Dimensions	12	0.914	> 0.70	Highly Reliable
Academic Anxiety	Cognitive	4	0.819	> 0.70	Reliable
Academic Anxiety	Affective/Emotional	4	0.854	> 0.70	Reliable
Academic Anxiety	Physiological	4	0.826	> 0.70	Reliable
Academic Anxiety	Behavioral	4	0.838	> 0.70	Reliable
Overall Academic Anxiety	4 Dimensions	16	0.907	> 0.70	Highly Reliable

Table 4. Results of the reliability test show that the HOTS instrument has an overall Cronbach's Alpha value of 0.914. At the same time, each of its dimensions yielded a coefficient of 0.842 for "analyzing," 0.867 for "evaluating," and 0.881 for "creating." These results indicate high internal consistency, meaning that the items used consistently measure the higher-order thinking skills of Civil Engineering students. Subsequently, a multivariate analysis was conducted to determine whether ChatGPT-assisted learning simultaneously influenced the Higher-Order Thinking Skills (HOTS) and academic anxiety of Civil Engineering students, after controlling for their initial

proficiency. In the MANCOVA analysis, post-test scores for HOTS and academic anxiety were designated as the dependent variables. In contrast, pre-test scores for HOTS and academic anxiety served as covariates to control for differences in initial proficiency between groups. The MANOVA test results are presented in Table 5.

Table 5. Descriptive Statistics of HOTS and Academic Anxiety by Learning Group

Dependent Variable	Learning Group	N	Pretest Mean $\pm$ SD	Posttest Mean $\pm$ SD	Mean Change
HOTS	ChatGPT-Assisted Learning	40	64.35 $\pm$ 7.42	84.68 $\pm$ 6.51	+20.33
HOTS	Conventional Learning	40	63.90 $\pm$ 7.18	73.45 $\pm$ 7.26	+9.55
Academic Anxiety	ChatGPT-Assisted Learning	40	72.60 $\pm$ 8.34	52.15 $\pm$ 7.48	-20.45
Academic Anxiety	Conventional Learning	40	71.85 $\pm$ 8.11	64.70 $\pm$ 8.03	-7.15

Table 5 shows that the group that received ChatGPT-assisted instruction experienced a greater increase in HOTS scores compared to the conventional learning group. The average HOTS score for the experimental group increased from 64.35 to 84.68, while that of the control group increased from 63.90 to 73.45. At the same time, academic anxiety in the experimental group decreased from 72.60 to 52.15, while in the control group it decreased only from 71.85 to 64.70. These findings provide preliminary evidence that ChatGPT-assisted learning has the potential not only to enhance higher-order thinking skills but also to reduce students' academic anxiety. Multivariate tests of the effect of ChatGPT-assisted learning on HOTS and academic anxiety Table 6.

Table 6. Multivariate Tests of the Effect of ChatGPT-Assisted Learning on HOTS and Academic Anxiety

Effect	Multivariate Test	Value	F	Hypothesis df	Error df	p-value	Partial η^2
Learning Model	Pillai's Trace	0.428	27.68	2	74	< 0.001	0.428
Learning Model	Wilks' Lambda	0.572	27.68	2	74	< 0.001	0.428
Learning Model	Hotelling's Trace	0.748	27.68	2	74	< 0.001	0.428
Learning Model	Roy's Largest Root	0.748	27.68	2	74	< 0.001	0.428

Table 6 shows a significant multivariate effect of the learning model on the combination of HOTS and students' academic anxiety. The results of Wilks' Lambda show $\Lambda = 0.572$, $F(2,74) = 27.68$, $p < 0.001$, partial $\eta^2 = 0.428$. Thus, the null hypothesis stating that there is no simultaneous difference between the experimental and control groups can be rejected. The partial η^2 value of 0.428 indicates that the learning model exerts a strong multivariate effect on the combination of the two dependent variables. In the context of this study, students who participated in ChatGPT-assisted learning exhibited a significantly different combined profile of HOTS and academic anxiety compared to students who participated in conventional learning after controlling for differences in initial scores. Furthermore, tests of between-subjects effects table 7.

Table 7. Tests of Between-Subjects Effects

Dependent Variable	Source	Adjusted Mean Difference	F	df	p-value	Partial η^2	Decision
HOTS	Learning Model	+10.84	38.72	1, 75	< 0.001	0.340	Significant
Academic Anxiety	Learning Model	-12.08	31.46	1, 75	< 0.001	0.295	Significant

Table 7 clarifies the sources of these multivariate effects. After controlling for pretest scores, ChatGPT-assisted learning had a significant effect on HOTS, with $F(1,75) = 38.72$, $p < 0.001$, partial $\eta^2 = 0.340$. The adjusted mean difference of +10.84 indicates that students in the ChatGPT group achieved higher HOTS scores than those in the conventional learning group.

4. Discussion

The research findings indicate that ChatGPT-assisted learning has a significant simultaneous effect on Higher Order Thinking Skills (HOTS) and academic anxiety among Civil Engineering students, as shown by the MANCOVA results (Wilks' Lambda = 0.572; $F(2,74) = 27.68$; $p < .001$; partial $\eta^2 = .428$). These results indicate that the integration of ChatGPT into the learning process is not only associated with changes in higher-order cognitive abilities but also with students' affective states. Specifically, the group that received ChatGPT-assisted learning demonstrated a greater increase in HOTS as well as a greater reduction in academic anxiety compared to the conventional learning group. These findings align with the meta-analysis by Deng et al. (2025), which found that ChatGPT interventions significantly enhanced higher-order thinking tendencies with a relatively large effect size ($g = 0.703$), in addition to improving students' academic performance and affective-motivational states. Thus, ChatGPT can be understood not merely as an information-providing tool, but as a cognitive and learning scaffold when its use is pedagogically designed (Sanjida Bibi et al., 2025).

The improvement in Civil Engineering students' HOTS in this study can be explained by ChatGPT's interactive characteristics, which allow students to engage in the processes of questioning, analyzing, evaluating, and refining the solutions they obtain (Huang et al., 2025). In the context of Civil Engineering, these processes are crucial because problem-solving relies not merely on the ability to recall formulas but requires the ability to analyze problem conditions, evaluate alternative solutions, and develop solutions based on various technical constraints. These research findings are further supported by Uddin et al. (2024), who investigated the use of ChatGPT among Civil Engineering students and found that students' responses after using ChatGPT became more comprehensive, detailed, and informative. Similarly, Lee et al. (2024) demonstrated that the use of ChatGPT, equipped with guidance mechanisms in blended learning, can support higher-order thinking skills (HOTS), self-regulated learning, and knowledge construction. This evidence reinforces the argument that ChatGPT's effectiveness in fostering HOTS is particularly evident when AI is used as a tool to facilitate exploration and reasoning, rather than as a substitute for students' own thinking processes (Al-Abyadh & Abdel Azeem, 2022).

The second important finding is that ChatGPT-assisted learning resulted in a greater reduction in academic anxiety compared to conventional learning. The between-subjects effect results showed a significant effect on academic anxiety ($F(1,75) = 31.46$; $p < .001$; partial $\eta^2 = .295$). From a pedagogical perspective, this finding can be explained by ChatGPT's ability to provide quick, responsive, and relatively personalized assistance when students face difficulties understanding concepts, assignments, calculations, or problem-solving (Yadisaputra, 2021). Access to immediate feedback has the potential to reduce the uncertainty and mental load that arise when students do not know how to begin or continue completing an assignment. This is consistent with Deng et al. (2025), who reported that the use of ChatGPT has a positive effect on affective-motivational states and significantly reduces mental effort. Abdallah et al. (2025) also concluded from their systematic review that ChatGPT can provide cognitive and emotional support, including indications of reduced test anxiety. However, uncontrolled use may also lead to technostress. Thus, the reduction in academic anxiety observed in this study can be understood as a result of students' increased access to learning support and feedback while tackling complex academic tasks.

Nevertheless, improvements in HOTS and a reduction in academic anxiety do not mean that the use of ChatGPT automatically results in better learning quality. The effectiveness of this technology heavily depends on pedagogical design, the quality of prompts, the ability to verify information, and students' active engagement. Li et al. (2026), through a systematic review of 67

empirical studies, found that ChatGPT most consistently supports critical and creative thinking when integrated into structured inquiry-based learning, supplemented by metacognitive regulation, argumentation, reflection, and idea-generation processes (Ningsih et al., 2023; Utomo et al., 2023). Conversely, the use of ChatGPT without a pedagogical framework can encourage cognitive offloading and cognitive dependence. These findings are important for civil engineering education because AI responses should not be accepted directly as final solutions. Students should be required to verify assumptions, evaluate the accuracy of procedures, compare AI responses with engineering principles and standards, and justify their chosen solutions.

Therefore, ChatGPT is more appropriately positioned as a dialogic cognitive partner rather than as a substitute for students' engineering reasoning (Li et al., 2026). Overall, this study expands the literature on the use of generative AI in higher education by demonstrating that ChatGPT-assisted learning has the potential to produce dual educational effects: strengthening the cognitive domain through enhanced higher-order thinking skills (HOTS) and strengthening the psychological domain through reduced academic anxiety. This contribution becomes increasingly relevant because Baig and Yadegaridehkordi (2024) indicate that research on ChatGPT in higher education has grown rapidly but still requires further exploration regarding its effective application across various disciplines. Furthermore, recent studies in engineering education indicate that prompting behavior, question efficiency, and problem-solving strategies when interacting with ChatGPT can predict student performance on engineering tasks, reinforcing that the quality of human-AI interactions is a critical component of learning outcomes (Hermanto et al., 2024; Mulyanto et al., 2018). Therefore, the main implication of this research is that universities, particularly Civil Engineering programs, need to integrate ChatGPT through a guided and critical AI-assisted learning approach, which involves the use of AI accompanied by structured prompting, answer verification, reflection, authentic problem-solving, and AI literacy. This approach enables students to reap the benefits of technology without compromising independent thinking, academic integrity, and engineering judgment, which are fundamental competencies for aspiring engineers (Putra et al., 2023).

5. Conclusion

This study found that ChatGPT-assisted learning significantly impacts the Higher-Order Thinking Skills (HOTS) and academic anxiety of Civil Engineering students. Students participating in ChatGPT-assisted learning demonstrated greater improvements in HOTS compared to those in conventional learning settings, specifically regarding their ability to analyze, evaluate, and create solutions for Civil Engineering problems. Concurrently, the use of ChatGPT was associated with reduced academic anxiety across cognitive, affective/emotional, physiological, and behavioral dimensions. Analysis results revealed significant effects on HOTS, $F(1,75) = 38.72$, $p < 0.001$, partial $\eta^2 = 0.340$, and on academic anxiety, $F(1,75) = 31.46$, $p < 0.001$, partial $\eta^2 = 0.295$. These findings confirm that ChatGPT has the potential to serve as an effective cognitive scaffold when integrated through instructional designs that are structured, critical, and focused on fostering higher-order thinking capabilities.

However, this study has certain limitations that must be acknowledged. First, the quasi-experimental design, lacking individual randomization, allows for the potential influence of uncontrolled variables. Second, the sample was limited to Civil Engineering students at a single institution; therefore, generalizing the findings to the broader context of engineering education requires caution. Third, the study did not deeply explore the quality of student interactions with ChatGPT, such as prompt quality, answer verification strategies, and the level of AI dependency,

factors that could moderate learning outcomes. Given these limitations, future research should employ fully randomized experiments with larger, more diverse samples and consider moderating variables such as AI literacy, learning styles, and students' prior knowledge. Further research also needs to qualitatively examine how students verify, evaluate, and reflect on ChatGPT outputs during engineering problem-solving processes, so that guidelines for AI integration can be formulated that are not only cognitively effective but also preserve students' independent thinking and academic integrity.

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