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Investigating the Effectiveness of AI-Based Innovative Mathematics Instruction on Learning Self-Regulation and Problem-Solving Thinking among Sixth-Grade Students

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ABSTRACT

Objective: The present study aimed to investigate the effectiveness of AI-based innovative mathematics instruction on learning self-regulation and problem-solving thinking among sixth-grade students at the Atomic Energy School in Bushehr.

Methods: This applied study employed a quasi-experimental pretest–posttest design with a control group. The statistical population consisted of all sixth-grade elementary school students at the Atomic Energy Elementary School in Bushehr during the 2025–2026 academic year (1404–1405). Using convenience sampling and based on the inclusion and exclusion criteria, 30 students were selected and randomly assigned to two groups — an experimental group and a control group, with 15 students in each. The educational intervention was implemented in six group-based sessions, each lasting 60–75 minutes, under teacher guidance and with controlled use of artificial intelligence.

Results: The findings showed that the adjusted mean of learning self-regulation in the experimental group was significantly higher than that of the control group. Therefore, after controlling for pretest scores, AI-based innovative mathematics instruction significantly improved students' learning self-regulation. Furthermore, the adjusted mean of problem-solving thinking in the experimental group was significantly higher than that of the control group, indicating that the educational intervention significantly enhanced the problem-solving thinking of sixth-grade students.

Conclusions: Based on the findings, it can be concluded that AI-based innovative mathematics instruction, when implemented purposefully, systematically, and under teacher guidance, has considerable potential to simultaneously enhance learning self-regulation and problem-solving thinking among elementary school students.

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Introduction

Technological developments over the past decade, particularly the emergence and expansion of artificial intelligence (AI), have brought about significant changes in the nature of teaching and learning. AI is no longer merely a computational technology; it has gradually become one of the influential components in designing learning environments, providing feedback, personalizing instruction, evaluating performance, and supporting learners' cognitive and metacognitive processes. This transformation is particularly important at the elementary level, since students at this stage are still forming their academic attitudes, learning strategies, educational autonomy, and basic cognitive skills. The systematic review by Aravantinos et al. (2024) showed that AI in elementary education has mainly been used to personalize learning, provide instructional support, foster engagement, and improve the learning experience. Mathematics, on the other hand, is a subject that, more than many others, requires high-level cognitive processes, reasoning, cognitive flexibility, strategy selection, and problem solving. The systematic review by Panqueban et al. (2024) showed that research on AI in mathematics education is rapidly increasing, and that intelligent systems and smart learning platforms are among the important applications of AI in this field.

Moreover, AI-based innovative mathematics instruction can be regarded as an educational approach in which the intelligent capabilities of technology are used to support the process of teaching and learning mathematics, tailor activities to learners' needs, provide immediate feedback, generate problems and learning situations, offer step-by-step guidance, and help teachers identify learning errors. In this approach, AI should not be regarded as a replacement for the teacher but rather as an instructional and cognitive tool alongside the teacher. The systematic review by Yoon et al. (2024) on AI-based mathematics teaching and learning showed that AI in mathematics education has been used in roles such as delivering instruction, supporting teachers, and assisting learners. Similarly, Son (2024), in a systematic review of intelligent tutoring systems in mathematics education, showed that intelligent systems can personalize part of the mathematics instruction process by providing instruction and feedback tailored to student performance. Likewise, Arriola-Mendoza and Valerio-Ureña (2024), in a systematic review of the factors affecting the implementation of AI tools in elementary schools, emphasized the necessity of appropriate instructional design, teacher readiness, infrastructure, equitable access, and ethical considerations. Furthermore, Mudjib et al. (2026), regarding the role of AI in mathematical problem solving and independent learning, showed that AI, when used appropriately, can support mathematics learning through scaffolding, immediate feedback, strategic guidance, and demonstration of the solution process.

On the other hand, learning self-regulation refers to a process in which the student actively sets learning goals, plans the path to achieving them, monitors their own performance during the learning activity, uses cognitive and metacognitive strategies, and finally evaluates the degree of their success and the appropriateness of the strategies used. A self-regulated student, therefore, is not simply someone who completes assignments, but a learner who can plan, control, evaluate, and revise their own learning process. Self-regulation is important in mathematics learning because solving mathematical problems requires a series of sequential decisions: the student must understand the problem, identify the objective, recognize relevant information, select an appropriate strategy, implement the solution, and then check the answer. Consequently, many self-regulatory processes directly overlap with the stages of problem solving. Huang et al. (2024), in a study of elementary students, showed that students' difficulties in solving mathematical word problems can be related to weaknesses in self-regulatory processes, and that providing appropriate feedback and guidance can support students' self-regulation during problem solving. Fattahi and Mousavi (2025), examining approaches to self-regulated learning in the era of generative AI, found that intelligent learning environments, generative tools, adaptive systems, and intelligent tutoring agents can play a role in personalizing the learning path and strengthening self-regulation; however, privacy, algorithmic bias, and excessive dependence on technology are among the major challenges in this field.

Problem-solving thinking, for its part, is one of the fundamental goals of mathematics education, since genuine mathematics learning occurs when students can apply their knowledge and skills in new, non-routine situations. Problem-solving thinking comprises a set of cognitive and metacognitive processes through which an individual understands a problem situation, extracts relevant information, sets a goal, selects an appropriate strategy, implements the solution, and finally evaluates the outcome. Problem solving therefore differs from mere calculation or the execution of a predetermined procedure. This skill is particularly important at the elementary level, since students at this stage must gradually move from solving purely algorithmic problems toward analyzing situations and selecting strategies. Recent research shows that self-regulation and mathematical problem solving are closely related. Ferreira et al. (2022) showed that self-regulated learning and working memory play an important role in the accuracy of mathematical problem solving, and that planning and control processes in particular can influence students' problem-solving performance. The systematic review by Liu et al. (2025) showed that a significant portion of AI applications in mathematics education relates to intelligent systems, assessment, and learning support; the researchers emphasize, however, that there is still insufficient study of the role of AI within theoretical frameworks of mathematics education and its deeper learning outcomes. Accordingly, the research value of AI-based innovative mathematics instruction increases when, instead of directly providing answers, the technology guides students to explain their solutions, compare strategies, identify errors, and evaluate their answers.

Regarding the relationship between AI-based innovative instruction, learning self-regulation, and problem-solving thinking, a coherent theoretical relationship can be drawn. Within this framework, AI-based innovative mathematics instruction functions as an instructional and environmental variable, learning self-regulation is one of the cognitive and metacognitive mechanisms influencing learning, and problem-solving thinking is an important cognitive and performance outcome of mathematics education. By providing immediate feedback, step-by-step guidance, tasks tailored to the student's level, and opportunities to revise answers, AI can create conditions in which students become more active in the process of planning, monitoring, and evaluating their learning. Increased self-regulation can, in turn, lead to improved problem-solving thinking through better planning, strategy selection, control of the solution process, and evaluation of answers. Research evidence indicates that AI in mathematics education can support problem solving through scaffolding, immediate feedback, and strategic guidance, and can foster independent learning through personalized pathways, pacing adjustments, and adaptive feedback; nevertheless, the number of studies that have simultaneously examined both problem-solving and self-regulated-learning outcomes remains limited (Kuo et al., 2026). It can therefore be argued that the effect of AI-based instruction on problem-solving thinking is probably not merely a direct effect, but that part of this effect may be realized through the strengthening of self-regulatory processes. In other words, if AI merely provides the answer to a problem, it may even reduce students' opportunity to think; but if, within an appropriate instructional design, it guides students to plan, ask questions, examine strategies, receive hints, correct errors, and evaluate solutions, it can provide a favorable environment for the development of self-regulation and, consequently, problem-solving thinking (Luo et al., 2026).

A review of domestic and international studies on this topic also showed that, within Iran, no study has directly examined the effectiveness of AI-based innovative mathematics instruction on students' learning self-regulation and problem-solving thinking; some studies have referred to it only implicitly in their introductions, and inconsistent results have been obtained. For example, Fattahi and Mousavi (2025), Yoon (2024), Panqueban (2024), Aravantinos (2024), Huang (2024), Yim (2024), Song (2025), and Xia (2026) have, in their respective studies, emphasized the effectiveness of AI-based innovative mathematics instruction on students' learning self-regulation and problem-solving thinking. Regarding the significance and necessity of the present study, several points can be noted. First, the sixth grade of elementary school is a sensitive stage in students' cognitive and academic development, during which students must, in addition to mastering mathematical concepts, acquire the ability to apply them in new, problem-oriented situations. Second, traditional methods of teaching mathematics do not always allow for continuous, individually tailored feedback, owing to limited class time and individual differences among students; AI, when used appropriately, can help reduce this limitation through rapid feedback, adaptive practice, and individualized support, and findings from recent reviews on elementary education confirm AI's capacity to personalize and make the learning environment more interactive. Third, the necessity of this research arises not only from the benefits of AI but also from the risks of its misuse: if students receive answers directly from the system instead of attempting to solve problems themselves, their opportunities for planning, reasoning, and self-assessment may diminish. From a practical standpoint, the findings of this study can be useful for sixth-grade teachers, instructional planners, e-content designers, and education officials; if the effectiveness of the proposed method is confirmed, models can be developed for designing mathematics lessons in which AI serves as a "learning scaffold" rather than providing final answers, and the results can also be applied in the design of teacher-empowerment courses.

Regarding the research gaps and the innovation of the present study, a review of recent sources shows that the first gap is the scarcity of studies that have simultaneously examined the three domains of AI, self-regulation, and mathematical problem solving. The second gap is the limited number of studies focused on the elementary level; studies on AI for the 4-to-12 age group remain limited and are scattered in terms of technology type, instructional objectives, and outcomes examined. The third gap is the scarcity of studies that have implemented AI as a designed teaching method grounded in learning theories, with researchers emphasizing the lack of clear theoretical frameworks for mathematics education. The fourth gap is the scarcity of intervention studies focused on the sixth grade of elementary school; much of the research on AI in education has been conducted at the secondary and university levels or has focused on teaching about AI rather than teaching with AI. Finally, an important gap in the Persian-language literature is the scarcity of experimental studies that have implemented an AI-based innovative mathematics teaching model in a real school setting while simultaneously measuring changes in elementary students' learning self-regulation and problem-solving thinking; recent Persian-language studies have mostly addressed the conceptual capacity of AI, intelligent learning, or self-regulation. The innovation of the present study can therefore be considered to lie in integrating the three components of intelligent technology, self-regulation, and problem-solving thinking in sixth-grade mathematics education, and in empirically examining the effect of an AI-based teaching model on these two important cognitive and metacognitive outcomes. Accordingly, the main research question addressed in this study is: Does AI-based innovative mathematics instruction affect the learning self-regulation and problem-solving thinking of sixth-grade students at the Atomic Energy School in Bushehr?

Material and Methods

The present study employed a quasi-experimental design with a pretest–posttest control-group design. The statistical population consisted of sixth-grade elementary students at the Atomic Energy School in Bushehr during the 2025–2026 academic year (1404–1405), from whom a sample of 30 students (15 in the experimental group and 15 in the control group) was selected through convenience sampling. After the sample was selected and participants were assigned to the experimental and control groups, the Learning Self-Regulation Questionnaire and the Problem-Solving Thinking Questionnaire were administered to all participants as a pretest. The inclusion criteria were: being enrolled in the sixth grade during the academic year under study, having parental informed consent, the student's own willingness and consent to participate, and regular class attendance with the ability to attend the scheduled instructional sessions. The exclusion criteria were: unexcused absence from more than two of the intervention sessions, failure to complete the pretest, posttest, or research questionnaires, and withdrawal of the student or parents from continued participation at any stage of the study. To maintain confidentiality and privacy, students' personal and academic information was kept confidential, and no names or identifying information were used in the analysis or reporting of results. The instruments used in the present study were as follows.

Learning Self-Regulation Questionnaire (Ryan & Connell, 1989):

The Ryan and Connell Learning Self-Regulation Questionnaire was designed based on self-determination theory. Its common version comprises 32 items rated on a four-point Likert scale ranging from "completely true" to "not at all true." Its components include external regulation (items 2, 6, 9, 14, 20, 24, 25, 28, and 32), introjected regulation (items 1, 4, 10, 12, 17, 18, 26, 29, and 31), identified regulation (items 5, 8, 11, 16, 21, 23, and 30), and intrinsic motivation (items 3, 7, 13, 15, 19, 22, and 27). The reliability of this questionnaire in the present study, using Cronbach's alpha, was 0.81. Its validity was assessed by calculating the correlation of each item with the total score, which showed that all items had a statistically significant correlation with the total score.

Problem-Solving Thinking Questionnaire (Heppner & Petersen, 1982):

To assess problem-solving thinking, the Problem-Solving Inventory developed by Heppner and Petersen — one of the most valid and widely used instruments — was used. This instrument measures individuals' perceptions of their problem-solving ability and process across three main components: Problem-Solving Confidence (PSC, 11 items), Approach–Avoidance Style (AA, 16 items), and Personal Control (PC, 5 items). Through this instrument, components such as problem comprehension, planning, strategy selection, strategy implementation, and answer review/evaluation can be assessed. The reliability of this questionnaire in the present study, using Cronbach's alpha, was 0.82. Its validity was assessed by calculating the correlation of each item with the total score, which showed that all items had a statistically significant correlation with the total score.

AI-Based Innovative Mathematics Instruction:

The instructional intervention in this study, titled "AI-Based Innovative Mathematics Instruction," was designed for sixth-grade elementary students across six instructional sessions, each lasting 60–75 minutes and conducted in groups under teacher guidance with controlled use of AI tools. The main basis of the intervention was Polya's four-stage problem-solving model — understanding the problem, devising a plan, carrying out the plan, and looking back — alongside attention to the core components of learning self-regulation (planning, monitoring, control, and self-evaluation) throughout the instructional process. In this intervention, AI was used as an instructional tool and learning companion, rather than as a replacement for the teacher or as a problem solver. The instructional content of the sessions was organized based on the sixth-grade mathematics curriculum, focusing on numbers and numerical patterns, fractions, decimal numbers, symmetry and coordinates, measurement, ratio and percentage, and estimation, such that the activities of each session, while covering the mathematical content, also provided appropriate opportunities to practice learning self-regulation and strengthen students' problem-solving thinking and skills (Liu et al., 2025).

Table 1. Summary of Session Content for AI-Based Innovative Mathematics Instruction (adapted from Liu et al., 2025)

Session	Objectives and content
Session 1: Numbers and numerical patterns	- Administer the posttest. General objective: Strengthen the ability to discover relationships, identify patterns, reason, and explain solutions. Behavioral objectives: By the end of the session, the student should be able to: • Identify a numerical pattern; • Explain the relationship between numbers; • Predict the next number in the pattern; • Explain their own solution for a pattern; • Review the answer generated by AI and determine whether it is correct. Implementation steps: Problem posing – 10 minutes The teacher presents the problem: Consider the pattern 3, 6, 12, 24, … What are the next two numbers? Explain the relationship between the numbers. Students first solve the problem individually, without using AI. Planning – 10 minutes The teacher asks students to answer: Where should I start? What relationship exists between the numbers? Should I add or multiply? How can I check my own answer? At this stage, students identify their goal and strategy. Interacting with AI – 15 minutes The teacher asks AI to pose guiding questions instead of providing the answer: "Help a sixth-grade student discover the relationship in the pattern 3, 6, 12, 24, but do not give the final answer — only ask guiding questions." The student compares AI's response with their own solution. Problem solving and discussion – 20 minutes New problem: Examine the numbers 2, 5, 10, 17, 26, … Find the next number and explain how you arrived at it. Students first solve the problem individually, then in pairs, and finally as a whole class. Self-evaluation – 10 minutes

	The student answers: Did I choose a strategy before solving the problem? Did I check my own answer? Did AI help me think better, or did it just give the answer? Assignment: The student designs a numerical pattern and asks AI to check it, without receiving the direct answer.
Session 2: Fractions	General objective: Strengthen conceptual understanding and problem-solving skill in adding, subtracting, multiplying, and dividing fractions. Main example: Ali had 3/4 of a cake. He gave 2/5 of the available cake to his friend. What portion of the whole cake did he give his friend? Understanding stage: The student identifies the given information, the unknown, and the relationship between the data. Planning stage: The student recognizes that finding "2/5 of 3/4" requires multiplying the fractions. AI-use stage: Teacher's controlled prompt: "Explain this problem to a sixth-grade student, but first ask what operation should be performed. Do not give the final answer until the student has explained their strategy." Solution: $3/4 \times 2/5 = 6/20 = 3/10$ AI then generates a similar problem: "Maryam has 2/3 liters of water and uses 3/5 of it. How much water was used?" The student solves it independently, then uses AI to review the process. Self-regulation activity: The student completes a table with four columns: My plan — What I did — The error I found — My correction.
Session 3: Decimal numbers	General objective: Strengthen the ability to calculate, estimate, and solve applied problems involving decimal numbers. Situational problem: A notebook costs 75.35 thousand tomans and a pencil costs 12.5 thousand tomans. If a student buys two notebooks and three pencils, what will the total cost be? The student must first analyze the problem and determine: $2 \times 75.35 + 3 \times 12.5$, then carry out the solution. AI activity: AI generates a similar, harder problem, but the student must provide their own solution before receiving feedback. Problem-solving-thinking activity: AI provides two different solutions to a problem — one correct, one containing an error. The student must: • Read both solutions; • Find the error in the incorrect one; • Explain the reason for the mistake; • Provide the correct solution. This activity is important because it transforms the student from a consumer of AI's answers into an evaluator and critic of them. Recent research also warns against directly delegating the problem-solving process to AI.
Session 4: Symmetry and coordinates	General objective: Strengthen spatial visualization, reasoning, situation analysis, and geometric problem solving. Opening activity: The teacher draws a coordinate plane and places point A at, e.g., A(2, 3). Question: If point A is reflected across the y-axis, what are the coordinates of the new point? The student answers first. AI is then asked: "Without giving the direct answer, use guiding questions to help the student understand the coordinates of the reflection of point (2, 3) across the y-axis." The student must first guess, then check AI's answer. Group activity: Each group creates a simple geometric shape on the coordinate plane and asks AI to: generate a similar shape; change the coordinates of the points; design a challenging question. Another group then solves the question created. Self-regulation: The student identifies: What did I know at first? What did I not know? What strategy did I use? How did I make sure my answer was correct?
Session 5: Ratio and percentage	General objective: Strengthen the ability to solve real, applied problems involving ratio, proportion, and percentage. This session is especially important, since percentage and ratio problems allow for realistic, multi-step, decision-oriented problems. Main problem: A bag costs 800 thousand tomans. The store offers a 15% discount. Calculate the discount amount and the final price. Students first solve the problem individually.

	Polya's strategy: Understanding: initial price = 800 thousand tomans; discount rate = 15%. Planning: first find 15% of the price. Execution: 800 × 15 ÷ 100 = 120; discount = 120 thousand tomans. Final price: 800 − 120 = 680 thousand tomans. AI stage: AI creates a new situation: "Design a realistic problem for a sixth-grade student about a 20% discount that requires at least two steps. Do not give the answer." Students solve it; AI then checks the student's answer rather than solving it itself. Critical-thinking activity: The teacher deliberately asks AI to give an incorrect answer. The student must identify AI's error. This is important, since recent research shows AI can be useful in mathematics education but has limits in complex reasoning, and there is a risk students become dependent on AI's answers.
Session 6: Estimation, integration, and multi-step problem solving	General objective: Integrate what was learned in earlier sessions and assess students' ability to independently use problem-solving strategies and self-regulation. Final integrative problem: The school wants to buy juice for 24 students. Each juice costs 37,500 tomans. The store offers a 10% discount on purchases over 800 thousand tomans. Does buying 24 juices qualify for the discount? Calculate the final price. The student must: extract the problem information; select an appropriate strategy; perform the calculation; check the answer by estimation; explain the result in their own words. AI stage: The student may use AI, but only for three types of requests: a. Requesting guidance: "I'm having trouble choosing a strategy. Just ask me one guiding question." b. Reviewing the solution: "Check my solution and only tell me whether there is an error; don't give the correct answer." c. Creating a similar problem: "Design a similar but slightly harder problem for a sixth-grade student." At the end, the student completes a brief self-regulation report: What was my goal? What strategy did I use? At which step did I struggle? Did I use AI? Did I check AI's answer? If I solved it again, what would I change? - Administer the posttest.

Results

To use parametric analysis-of-covariance tests, the assumption of normality of the variables was first examined using the Kolmogorov–Smirnov test, the results of which are presented in Table 2.

Table 2. Kolmogorov–Smirnov Test Results for the Normality Assumption

Variable	Group	Statistic	P
Learning self-regulation	Experimental group	0.123	0.2
	Control group	0.196	0.2
Problem-solving thinking	Experimental group	0.311	0.2
	Control group	0.287	0.2

The results of the Kolmogorov–Smirnov test in Table 2 showed that the significance level for both the learning self-regulation and problem-solving thinking variables, in both the experimental (under AI-based innovative mathematics instruction) and control groups, was greater than 0.05. The Kolmogorov–Smirnov statistic was therefore not significant at the 0.05 error level, indicating that the variables are normally distributed.

Table 3. One-Way Analysis of Covariance for the Effect of AI-Based Innovative Mathematics Instruction on Learning Self-Regulation

Source of variation	SS	DF	MS	F	P	η^2	Power
Pretest	5392.21	1	5392.21	66.91	0.001	0.644	1
Group	794.66	1	794.66	9.86	0.003	0.210	1

The results of the analysis of covariance in Table 3 showed that, after controlling for the effect of the pretest, there was a significant difference between the experimental and control groups in learning self-regulation ($F = 9.86$, $p = 0.003$). Thus, the effect of group on learning self-regulation, after controlling for pretest scores, is significant, confirming the hypothesis regarding the effect of AI-based innovative mathematics instruction on learning self-regulation. The eta-squared value was 0.210, indicating that, after controlling for pretest scores, approximately 21% of the variance in learning self-regulation is associated with the group effect. The observed statistical power (1) indicates an adequate sample size and high confidence in detecting the intervention effect. To determine the direction and magnitude of the difference, pairwise comparisons were conducted using the Bonferroni test, the results of which are presented in Table 4.

Table 4. Pairwise Comparisons of Adjusted Means of Learning Self-Regulation Between the Experimental and Control Groups

Variable	Group	Mean	Std. error	Mean difference	P
Learning self-regulation	Experimental	96.48	2.00	8.91	0.003
	Control	87.56	2.00		

The Bonferroni post hoc comparisons in Table 4 showed that the estimated adjusted mean of learning self-regulation in the experimental group was significantly higher than that of the control group, with a mean difference of 8.91 points ($p < 0.003$). Thus, after controlling for pretest scores, AI-based innovative mathematics instruction significantly improved the learning self-regulation of students in the experimental group compared with the control group.

Table 5. One-Way Analysis of Covariance for the Effect of AI-Based Innovative Mathematics Instruction on Problem-Solving Thinking

Source of variation	SS	DF	MS	F	P	η^2	Power
Pretest	5788.94	1	5788.94	52.43	0.001	0.586	1
Group	3774.02	1	3774.02	34.18	0.001	0.480	1

The results of the one-way analysis of covariance in Table 5 showed that, after controlling for the effect of the pretest, there was a significant difference between the experimental and control groups in problem-solving thinking ($F = 34.18$, $p = 0.001$). Thus, the effect of group on problem-solving thinking, after controlling for pretest scores, is significant, confirming the hypothesis regarding the effect of AI-based innovative mathematics instruction on problem-solving thinking. The eta-squared value was 0.480, indicating that, after controlling for pretest scores, approximately 48% of the variance in problem-solving thinking is associated with the group effect. The observed statistical power (1) indicates an adequate sample size and high confidence in detecting the intervention effect. To determine the direction and magnitude of the difference, pairwise comparisons were conducted using the Bonferroni test, the results of which are presented in Table 6.

Table 6. Pairwise Comparisons of Adjusted Means of Problem-Solving Thinking Between the Experimental and Control Groups

Variable	Group	Mean	Std. error	Mean difference	Sig.
Problem-solving thinking	Experimental	166.32	2.35	19.44	0.001
	Control	146.87	2.35		

The Bonferroni post hoc comparisons in Table 6 showed that the estimated adjusted mean of problem-solving thinking in the experimental group was significantly higher than that of the control group, with a mean difference of 19.44 points ($p < 0.001$). Thus, after controlling for pretest scores, AI-based innovative mathematics instruction significantly improved the problem-solving thinking of students in the experimental group compared with the control group.

Discussion

The aim of this study was to examine the effectiveness of AI-based innovative mathematics instruction on learning self-regulation and problem-solving thinking among sixth-grade students at the Atomic Energy School in Bushehr. The results showed that the estimated mean of learning self-regulation in the experimental group was significantly higher than that of the control group; thus, after controlling for pretest scores, AI-based innovative mathematics instruction significantly improved the learning self-regulation of students in the experimental group compared with the control group. The results also showed that the estimated mean of problem-solving thinking in the experimental group was significantly higher than that of the control group; thus, after controlling for pretest scores, AI-based innovative mathematics instruction significantly improved the problem-solving thinking of students in the experimental group compared with the control group. These findings are consistent with those obtained in the studies of Fattahi and Mousavi (2025), Yoon (2024), Panqueban (2024), Aravantinos (2024), Huang (2024), Yim (2024), Song (2025), and Xia (2026). An explanation of the findings suggests that AI-based innovative mathematics instruction, by providing an interactive, personalized, and feedback-oriented environment, can strengthen students' learning self-regulation. In this approach, unlike traditional instruction, the student is not merely a passive recipient of information but plays an active role in the learning process, and must analyze the problem, define their objective, and select an appropriate strategy before using AI. The student then monitors their own performance while receiving step-by-step guidance and feedback from AI, and revises their strategy if an error is observed. This process aligns with the core components of self-regulated learning — planning, monitoring, control, and self-evaluation. In this regard, Luo et al. (2026) showed that purposeful human–AI collaboration can improve elementary students' self-regulation and mathematics performance, particularly when students use AI for reasoning, self-explanation, and reviewing the learning process rather than receiving direct answers. Similarly, Xia et al. (2026), in their systematic review, stated that generative AI can support self-regulatory processes through personalizing learning, providing feedback, supporting goal-setting, monitoring progress, and suggesting learning strategies. Accordingly, the increased self-regulation observed in the experimental group may be attributed to the fact that the structure of the intervention guided students to plan before solving problems, monitor their performance during problem solving, and evaluate and revise their answers afterward.

The finding regarding improved problem-solving thinking, in turn, can be explained by the problem-centered nature of the intervention. In AI-based innovative instruction, instead of focusing solely on memorizing rules and performing calculations, students encountered varied and applied problems and analyzed and solved them within the framework of Polya's four stages — understanding the problem, devising a plan, carrying out the plan, and looking back. AI functioned in this process as a cognitive scaffold, providing students with greater opportunities to test different strategies and correct errors by posing guiding questions, offering similar examples, comparing solutions, and giving feedback. This explanation is consistent with the findings of Liu et al. (2025), who showed that a generative-AI-based learning environment can improve elementary students' performance in solving mathematical word problems. Similarly, Kuo et al. (2026) showed that an AI-based learning companion, particularly when combined with problem-solving strategies and Socratic dialogue, can support elementary students' mathematical problem-solving process. Other recent studies likewise confirm that the purposeful use of AI tools in mathematics classrooms can enhance students' mathematics performance and problem-solving ability, and that targeted instructional interventions for solving mathematical word problems at the elementary level have a favorable capacity to improve students' problem-solving performance. Overall, it appears that combining AI, self-regulatory strategies, and step-by-step problem-solving instruction within a single instructional framework is the most important reason for the effectiveness of the present intervention on students' problem-solving thinking.

Finally, it can be concluded that combining AI-based mathematics instruction with self-regulatory strategies and Polya's problem-solving model can be an effective approach for simultaneously enhancing the cognitive and metacognitive abilities of elementary students. The strength of this approach is that it transforms the student from a passive recipient of answers into an active learner, analyst, and evaluator, while, alongside the use of AI's capabilities, preserving the role of independent thinking and teacher supervision. Accordingly, the planned and instructional use of AI can be considered one of the innovative approaches in elementary mathematics education; however, its effectiveness depends on the quality of instructional design, the digital literacy of both teacher and student, the type of interaction with AI, and preventing students from becoming dependent on ready-made answers. In conclusion, AI-based innovative mathematics instruction, when implemented purposefully, systematically, and under teacher guidance, can be an effective approach for simultaneously enhancing the learning self-regulation and problem-solving thinking of sixth-grade elementary students. The results of the present study showed that the instructional and controlled use of AI's capabilities does not merely increase students' ability to perform calculations and arrive at correct answers, but can also strengthen deeper learning processes, including planning for problem solving, selecting appropriate strategies, monitoring the learning process, identifying and correcting errors, evaluating answers, and reflecting on solutions. In such an environment, before receiving help from AI the student attempts to analyze the problem independently, and after receiving guidance is also required to check the accuracy of the answer and the suggestion provided; thus, AI is transformed from a mere answer-providing tool into a cognitive and instructional scaffold that guides and strengthens the student's thinking process.

The study was conducted among sixth-grade elementary students at Atomic Energy schools in Bushehr; therefore, generalizing the results to students in other grades, schools, and geographic regions should be done with caution. It is accordingly recommended that elementary teachers, particularly mathematics teachers, use the capabilities of AI purposefully, gradually, and under instructional supervision, and that instead of using AI merely to provide answers, they use it to create problems, provide step-by-step guidance, generate varied examples, offer feedback, compare solutions, and strengthen students' self-evaluation. It is also recommended that, in designing classroom activities, sufficient opportunity be given to students for planning, monitoring their learning, correcting errors, and reviewing answers, so that the use of AI does not lead to dependency but instead serves the development of self-regulation and independent thinking. In addition, it appears necessary to hold training courses and empowerment workshops for teachers on AI literacy, designing instructional prompts, evaluating the accuracy of AI-generated responses, and methods of integrating AI with problem-solving and self-regulation strategies. It is also recommended that schools provide appropriate infrastructure and develop clear guidelines for the responsible use of AI, so as to create conditions for the safe and effective use of this technology. Finally, given the positive results of the present study, it is recommended that future research examine the effectiveness of this instructional approach across different grade levels, other subjects, different groups of students, and longer time periods, and, in addition to self-regulation and problem-solving thinking, also examine variables such as academic motivation, creativity, critical thinking, deep learning, and students' attitudes toward AI.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of Islamic Azad University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All authors contributed to the study conception and design, material preparation, data collection, and analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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