



## Exploring the Relationship between Problem Solving and Metacognition in Problem-Based Learning: A Case Study with Secondary School Students

Le Chi Nguyen<sup>1</sup>, Nguyen Thi Thuy Quynh<sup>2</sup>, Nguyen Thi Ha<sup>3</sup>

<sup>1,2,3</sup> Faculty of Education, VNU University of Education, Hanoi, Vietnam

<sup>2</sup>ORCID: <https://orcid.org/0000-0002-7565-0206>

<sup>3</sup>ORCID: <https://orcid.org/0009-0008-0788-2065>

**ABSTRACT:** This study investigated the effects of problem-based learning (PBL) on secondary students' metacognitive regulation and examined its relationship with problem-solving processes. Despite extensive research on PBL, limited empirical evidence exists on how it fosters metacognitive regulation at the secondary level and how these processes interact with the problem-solving stages.

A quasi-experimental pretest-posttest design was conducted with 128 Grade 10 students assigned to a PBL group and a traditional instruction group for comparison. Metacognitive skills were measured using an adapted Metacognitive Awareness Inventory (MAI) questionnaire. Data were analyzed using analysis of covariance (ANCOVA), Pearson correlations, and confirmatory factor analysis (CFA).

The results indicate that PBL significantly improves students' metacognitive regulation after controlling for baseline differences, with moderate-to-large effect sizes. Correlation and regression analyses revealed consistent associations between metacognitive processes and the corresponding problem-solving stages, particularly planning, monitoring, and evaluation. The CFA results confirmed the validity of the measurement model.

These findings suggest that metacognitive regulation is a key mechanism through which PBL enhances problem-solving performance, highlighting the importance of integrating explicit metacognitive scaffolding into secondary science education.

**Corresponding Author:**

**Le Chi Nguyen**

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### INTRODUCTION

In today's rapidly evolving knowledge society, students are increasingly expected to acquire disciplinary knowledge and regulate their own learning to adapt, innovate, and solve complex problems. Metacognition, defined as the awareness and regulation of one's cognitive processes, plays a central role in enabling learners to plan, monitor, and evaluate their thinking (Flavell, 1976; Schraw & Dennison, 1994). Numerous studies have shown strong links between metacognition and academic performance, particularly in complex problem-solving tasks, where learners must strategically allocate cognitive resources and reflect on their progress (Veenman et al., 2006; Efklides, 2008).

Problem-solving competence has similarly been recognized as a core 21st-century skill. Classical models, such as Polya's (1945) four-step framework and later information-processing perspectives (Newell & Simon, 1972), highlight that effective problem solving requires not only cognitive strategies but also metacognitive regulation, such as identifying the problem, selecting strategies, monitoring execution, and evaluating the outcomes. This interdependence suggests that metacognition is both a prerequisite for and an outcome of problem-solving processes.

Among contemporary instructional approaches, problem-based learning (PBL) provides an ideal context for cultivating metacognition and problem solving. Originating in medical education (Barrows, 1986), PBL requires students to analyze ill-structured problems, determine what they need to learn, plan inquiries, collaborate with peers, and evaluate emerging solutions (Hmelo-Silver, 2004). As students iterate through these cycles, they practice core metacognitive processes such as planning learning goals, monitoring group progress, and reflecting on the adequacy of their strategies. Previous research has demonstrated PBL's positive impact of PBL on problem-solving performance, motivation, and deeper understanding (Bezanilla et al., 2021; Strobel & van Barneveld, 2009).

However, despite extensive studies on PBL's impact of PBL on learning outcomes, relatively little is known about how PBL specifically develops metacognitive regulation, especially at the secondary school level. Existing research often treats metacognition as a background or indirect variable rather than a focal construct (Veenman, 2012). In addition, few empirical studies have examined the reciprocal relationships between metacognitive processes (planning, monitoring, and evaluation) and problem-solving stages (problem identification, planning procedures, and evaluating solutions) within PBL environments. Understanding these relationships is theoretically important, as metacognition may not only mediate the effectiveness of PBL but also serve as a mechanism that enables students to transfer problem-solving skills to new contexts.

## LITERATURE REVIEW

Metacognition and problem solving have long been recognized as essential competencies for effective learning in the 21st century. Metacognition refers to learners' ability to plan, monitor, and evaluate their cognitive processes (Flavell, 1976; Schraw & Dennison, 1994). Within self-regulated learning (SRL), metacognition is viewed as a central mechanism that directs cognitive strategies, helps learners manage cognitive load, and supports reflective thinking (Zimmerman 2002). Empirical studies have consistently shown that higher metacognitive awareness is associated with a deeper understanding, improved academic achievement, and better performance in inquiry-based or ill-structured tasks (Veenman et al., 2006; Zohar & Barzilai, 2013).

**Metacognition and Self-Regulated Learning:** Metacognition comprises two major components: metacognitive knowledge (declarative, procedural, and conditional) and metacognitive regulation (planning, monitoring, and evaluating) (Schraw & Moshman, 1995). These regulatory processes enable learners to set goals, select strategies, track comprehension, and revise approaches when necessary. In secondary education, explicit metacognitive behaviors, such as self-questioning, progress checking, and self-assessment, significantly contribute to students' ability to manage complex reasoning tasks (Efklides, 2008; Dignath & Büttner, 2018). Thus, metacognition is both a target of instruction and a mechanism that enhances learners' engagement and adaptive expertise.

**Problem-solving processes and the role of metacognition:** Problem-solving is a foundational cognitive activity in science education, and classical models, such as Polya's (1945) four-step framework, which includes understanding the problem, planning a solution, executing the plan, and evaluating the results, provide a structured approach to solving tasks. Later information-processing perspectives conceptualize problem solving as a system involving strategy selection, hypothesis testing, and reflective evaluation (Newell & Simon, 1972). Across these models, metacognition plays a necessary role. Learners must monitor their progress, detect errors, and adjust strategies to achieve successful outcomes (Davidson & Sternberg, 1998). Jonassen (2000) further argues that metacognitive flexibility is particularly important for solving ill-structured problems because such tasks often lack clear goals, require integration of multiple knowledge sources, and involve uncertainty. Empirical findings confirm that students who actively plan, monitor, and evaluate their thinking perform better on open-ended or inquiry-oriented tasks than those who rely only on cognitive strategies (Veenman et al., 2006).

**Problem-Based Learning as a Context for Developing Metacognition:** Problem-based learning (PBL) provides an instructional environment in which metacognition and problem-solving naturally interact. Originally developed for medical education (Barrows, 1986), PBL immerses learners in authentic, ill-structured problems that require analysis, hypothesis generation, research, collaboration, and reflection (Hmelo-Silver, 2004). As students cycle through identifying what they know, determining what they need to learn, investigating solutions, and evaluating outcomes, they enact core metacognitive regulatory processes. Research has shown that PBL enhances deep learning, student motivation and problem-solving performance (Norman & Schmidt, 1992; Strobel & van Barneveld, 2009). Studies in science education have indicated that PBL supports the explicit development of metacognitive skills. For example, Sungur and Tekkaya (2006) found that high school students in PBL environments significantly improved their planning and monitoring behaviors compared to those receiving traditional instruction.

Despite its potential, research on PBL's impact on metacognition at the secondary level remains limited. Much of the existing work focuses on higher education or considers metacognition an indirect variable rather than a core learning outcome (Veenman, 2012). Moreover, while theoretical models suggest strong reciprocal relationships between metacognitive processes (planning, monitoring, evaluating) and specific problem-solving steps (problem identification, planning procedures, evaluating solutions), few empirical studies have investigated these interdependencies. In particular, there is a lack of quantitative research

using validated instruments, such as the Metacognitive Awareness Inventory (MAI), combined with correlation and confirmatory factor analysis (CFA) to explore these constructs in PBL settings.

Overall, prior literature demonstrates that metacognition enhances students' strategic engagement in problem solving, and problem-solving tasks provide rich opportunities for metacognitive regulation. PBL, as a constructivist pedagogy, integrates these two processes by engaging students in iterative cycles of inquiry and reflection. However, current research has not sufficiently examined (a) how metacognitive regulation correlates with specific problem-solving stages in secondary PBL contexts, (b) how these relationships unfold during instruction, and (c) whether PBL produces measurable improvements in students' metacognitive skills compared to traditional teaching. Addressing these gaps is essential for understanding metacognition as both an outcome and a mechanism of PBL, and for designing instructional models that intentionally scaffold students' self-regulated learning.

To address these gaps, this study investigates the relationship between metacognitive regulation and problem-solving performance among secondary school students engaged in PBL. Using the Metacognitive Awareness Inventory (Schraw & Dennison, 1994) and a quasi-experimental design, the study examines changes in students' metacognitive skills, the strength of associations between metacognitive and problem-solving components, and the reciprocal interactions between these constructs. This study was guided by the following three research questions:

**RQ1.** To what extent do students' metacognitive regulation skills (planning, monitoring, and evaluating) correlate with their problem-solving performance in a PBL context?

**RQ2.** What are the reciprocal relationships between specific problem-solving steps and metacognitive processes in PBL?

**RQ3.** Do students' metacognitive skills improve significantly after participating in PBL activities compared with traditional instruction?

By answering these questions, this study clarifies the dual role of metacognition as both an outcome and a mechanism of PBL. The findings provide empirical evidence for designing PBL environments that intentionally scaffold metacognitive processes, thereby supporting competency-based educational reforms and preparing students for adaptive, reflective learning in complex 21st-century contexts.

## THEORETICAL BACKGROUND

**Problem-Based Learning:** Problem-Based Learning (PBL) was first developed at McMaster University in the late 1960s as an instructional approach that immerses learners in authentic, ill-structured problems requiring reasoning, inquiry, and collaboration (Barrows and Tamblyn, 1980). Since then, PBL has been widely adopted across medicine, engineering, the natural sciences, and secondary education because of its ability to promote deeper conceptual understanding and learner autonomy (Tan, 2003; Nguyen, 2025).

Early comparative studies demonstrated that PBL enhances learners' motivation, self-direction, and teamwork more effectively than traditional lecture-based instruction (Norman & Schmidt, 1992). Subsequent research has focused on identifying the mechanisms underlying PBL's effectiveness, revealing its strong alignment with inquiry, conceptual restructuring and reflective learning (Hmelo-Silver, 2004; Savery, 2006). Contemporary perspectives further conceptualize PBL as a competency-based pedagogy that develops 21st-century skills, such as collaboration, critical thinking, creativity, and metacognition (Loyens, Magda, & Rikers, 2008).

Although the specific models vary, PBL typically follows cyclical stages.

- (1) identifying and analyzing a problem;
- (2) Determining what learners know and what they need to learn
- (3) Conducting self-directed research
- (4) synthesizing information through group discussion; and
- (5) Evaluating and presenting solutions (Barrows 1986; Schmidt 1993).

Throughout these cycles, teachers act as facilitators, guiding questioning, prompting deeper reasoning, monitoring group interactions, and fostering reflection, rather than directly delivering content (Hmelo-Silver, 2004). Assessments in PBL often integrate peer evaluation, formative feedback, and group presentations, emphasizing both the processes and products.

In science education, PBL has been shown to strengthen critical thinking and problem-solving skills by situating learning in real-world contexts (Hmelo-Silver, 2004; Lonka, 2018). Its iterative cycles of generating, testing, and refining ideas also help learners perceive unsuccessful attempts not as failures but as opportunities for improvement, a process closely aligned with metacognitive development (Kolodner, 2002).

Problem solving is a fundamental cognitive process in which learners interpret problems, design strategies, execute actions, and evaluate outcomes. Classical frameworks, such as Polya's (1945) four-step model (understand → plan → execute → evaluate), emphasize structured reasoning, whereas information-processing theories (Newell & Simon, 1972) highlight the iterative and dynamic nature of problem-solving.

Across these models, metacognitive regulation plays a central role in determining the quality of students' problem-solving performance. Metacognition encompasses the processes of planning, monitoring, and evaluating one's thinking (Schraw and Dennison 1994).

Planning supports goal setting, activation of prior knowledge, and strategy selection.

Monitoring enables learners to track their progress, detect errors, and make adjustments during strategy execution.

Evaluation helps learners judge the adequacy of solutions and identify opportunities for improvement.

Research consistently demonstrates that students who exhibit stronger metacognitive regulation are more effective at identifying key elements of a problem, justifying decisions, responding to uncertainty, and refining strategies (Veenman et al., 2006; Zohar & Barzilai, 2013). Thus, metacognition enhances problem-solving performance and shapes how students learn from complex tasks.

**The Relationship Between Problem Solving and Metacognition:** Metacognition, first conceptualized by Flavell (1976) as awareness and regulation of one's cognitive processes, has become central to theories of self-regulated learning (Zimmerman, 2002; Pintrich, 2004) and is recognized as a key competence for lifelong learning in modern knowledge-based societies (OECD, 2018). Metacognition consists of two major components: metacognitive knowledge and metacognitive regulation (Schraw & Moshman, 1995).

Metacognitive knowledge includes declarative knowledge (understanding one's strengths and weaknesses as a learner), procedural knowledge (knowing how to apply strategies), and conditional knowledge (understanding when and why to use strategies).

Metacognitive regulation encompasses three core processes: planning (goal setting and strategy selection), monitoring (tracking comprehension and performance), and evaluation (assessing outcomes and reflecting on strategy effectiveness) (Efklides, 2008; Veenman et al., 2006). A substantial body of empirical evidence highlights the strong relationship between metacognition and learning outcomes. Veenman et al. (2006) describe metacognition as a "bridge" between prior knowledge and problem-solving performance. In PBL environments, metacognitive regulation supports both individual engagement and collaborative group learning by helping students articulate goals, check progress, and adjust strategies during inquiry cycles (Hmelo-Silver, 2004). Research in secondary contexts has shown that explicit metacognitive behaviors—self-questioning, progress checking, and self-assessment—are strongly associated with higher-order problem-solving performance (Zohar & Barzilai, 2013; Dignath & Büttner, 2018).

Problem-solving has long been a focus of cognitive science research. Polya (1945) proposed a four-step process (understanding, planning, implementing, evaluating), while Newell and Simon (1972) conceptualized problem solving as an information-processing system in which learners apply and revise strategies. Later studies have shown that cognitive strategies alone are insufficient; successful problem-solving requires metacognitive oversight to monitor progress, detect errors, and revise actions (Davidson & Sternberg, 1998). Jonassen (2000) further noted that metacognition becomes particularly important in ill-structured problems, which involve uncertainty, multiple solutions, and incomplete information.

**Table 1** synthesizes the foundational and empirical studies supporting this relationship. Foundational works (Flavell, 1976; Schraw & Dennison, 1994) defined metacognition and validated its measurement. Studies in PBL contexts (Hmelo-Silver, 2004; Sungur & Tekkaya, 2006) have demonstrated that PBL activities naturally promote planning, monitoring, and reflection. Reviews by Veenman et al. (2006) and Zohar and Barzilai (2013) confirmed metacognition as an integral component of scientific problem solving, whereas recent classroom-based research (Dignath & Büttner, 2018) has shown that teacher practices that encourage metacognitive questioning lead to improved student regulation.

**Table 1. Key Empirical and Foundational Studies on Metacognition in PBL Contexts**

Author(s) & Year	Context / Participants	Instrument / Method	Key Findings
Flavell (1976)	Theoretical foundation	Conceptual analysis	introduced the concept of metacognition as the awareness and regulation of cognition.
Schraw & Dennison (1994)	University students (USA)	MAI – Metacognitive Awareness Inventory	Two metacognitive components were validated: knowledge and regulation.
Hmelo-Silver (2004)	PBL in science & medical education	Case studies; observations	PBL promotes monitoring, reflection and collaborative reasoning.
Sungur & Tekkaya (2006)	High school science classes (Turkey)	Pre-post tests; questionnaires	PBL students improved their planning and monitoring compared to traditional classes.
Veenman et al. (2006)	Cross-disciplinary review	Systematic review	Metacognition was identified as a "bridge" between knowledge and problem-solving.
Zohar & Barzilai (2013)	Science education studies	Systematic literature review	Metacognitive instruction enhances inquiry and scientific problem solving.

Despite this strong evidence base, few studies have systematically examined the interrelationships between problem-solving steps and metacognitive regulation in secondary-level PBL environments. The present study addresses this gap by investigating how PBL fosters metacognitive development and how metacognitive processes support students' engagement in complex problem-solving tasks. Recent reviews (Zohar & Barzilai, 2013) emphasize that metacognition is not only supportive but also integral to problem-solving, especially in inquiry-based and PBL environments. This theoretical lens highlights the importance of examining how specific problem-solving stages interact with metacognitive processes. Building on the literature, the present study proposes an integrated conceptual model (Figure 2) that connects PBL, problem-solving stages, and

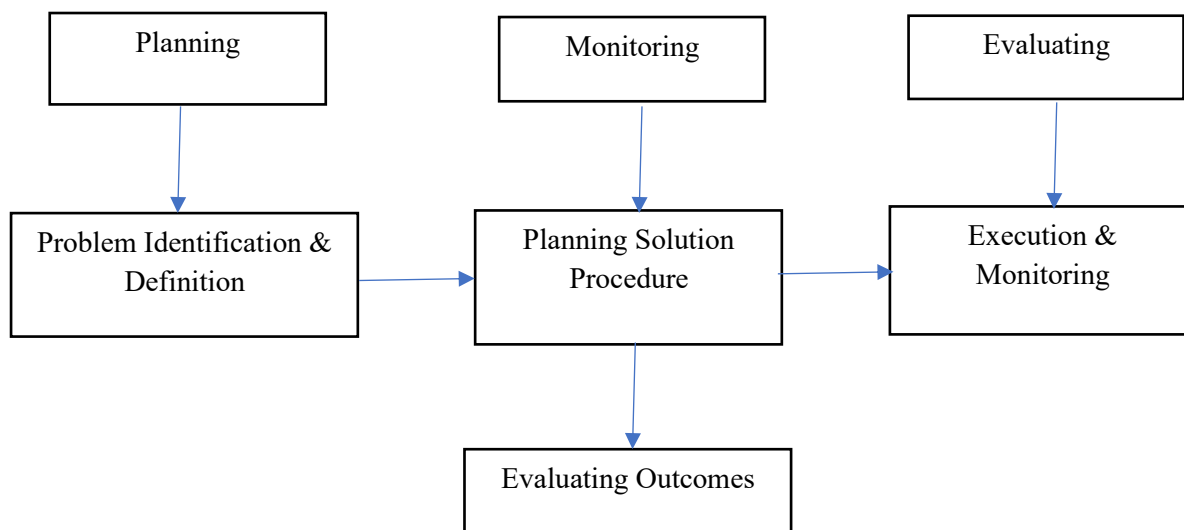
**Figure 1** presents a bidirectional model that illustrates how metacognitive regulation (planning, monitoring, and evaluation) interacts with problem-solving stages (problem identification, planning procedures, executing strategies, and evaluating outcomes) within the PBL cycle.

At the problem-identification stage, students activate prior knowledge and clarify goals, which aligns with metacognitive planning, including setting objectives and selecting initial strategies.

During the planning-solution stage, both planning and monitoring processes are engaged as learners design procedures, anticipate difficulties, and adjust their plans accordingly.

Throughout the execution stage, monitoring functions as a continuous feedback loop, enabling students to compare their progress with their goals and modify their actions as new information emerges.

In the evaluation-of-outcomes stage, students apply metacognitive evaluation by judging the effectiveness of their solutions and reflecting on improvements for future tasks.



**Figure 1. Integrated Model of Metacognition and Problem Solving in a PBL Environment**

**Source.** Adapted from Based on Jonassen (2000) and Schraw & Dennison (1994)

The PBL context, shown as an outer ring in the figure, provides ill-structured problems and iterative inquiry cycles that continuously activate these metacognitive processes. Through repeated engagement in these cycles, students enhance both problem-solving competence and metacognitive regulation, illustrating the reciprocal relationship proposed by this model.

#### 4. METHOD

**Research Design and Participants:** This study employed a quasi-experimental pretest–posttest design with two intact Grade 10 classes (N = 128) assigned to an experimental group (PBL) and a control group (traditional instruction) for comparison. The intervention lasted six weeks. The experimental group engaged in structured PBL cycles, whereas the control group received teacher-centered instruction that covered the same content.

**Instruments:** Metacognitive skills were measured using an adapted Metacognitive Awareness Inventory (MAI) (Schraw & Dennison, 1994), which consists of metacognitive knowledge and regulation components (Table 2). The instrument was adapted through expert validation and pilot testing (n = 60) to ensure its contextual appropriateness. Problem-solving performance was assessed using tasks aligned with Pólya's framework.

**Data Collection and Analysis:** Pre- and post-tests were administered before and after the intervention. To examine the effects of PBL, ANCOVA was conducted using post-test scores as the dependent variable and pre-test scores as covariates. Pearson's correlation and multiple regression analyses were used to examine the relationship between metacognition and problem-solving. CFA was conducted to validate the measurement models.

## 5. RESULTS

The structure of the Metacognitive Awareness Inventory (MAI) is shown in Table 2. As shown in Table 3, all subscales demonstrated satisfactory reliability and convergent validity ( $\alpha = 0.81\text{--}0.88$ ;  $CR > 0.80$ ;  $AVE > 0.50$ ), indicating that the instrument was appropriate for subsequent analysis.

**Table 2. Structure of the Metacognitive Awareness Inventory (MAI)**

Component	Subcomponent	Description	No. of Items
Metacognitive Knowledge	Declarative knowledge	Knowing about oneself as a learner; understanding strengths and weaknesses	8
Metacognitive Knowledge	Procedural knowledge	Knowing how to use learning strategies	11
Metacognitive Knowledge	Conditional knowledge	Knowing when and why strategies should be used	7
Metacognitive Regulation	Planning	Goal-setting, strategy selection, planning before learning	10
Metacognitive Regulation	Monitoring	Checking understanding and adjusting learning processes	9
Metacognitive Regulation	Evaluating	Assessing outcomes, reflecting on strategy effectiveness	7
Total	—	—	52

Prior to testing the research hypotheses, the psychometric properties of the adapted MAI were assessed. Reliability was evaluated using Cronbach's alpha, and convergent validity was examined using composite reliability (CR) and average variance extracted (AVE).

**Table 3. Reliability and Validity Indices for the MAI Components**

Component	Subcomponent	No. of Items	Cronbach's Alpha ( $\alpha$ )	Composite Reliability (CR)	Average Variance Extracted (AVE)
Metacognitive Knowledge	Declarative knowledge	8	0.83	0.86	0.56
Metacognitive Knowledge	Procedural knowledge	11	0.87	0.89	0.58
Metacognitive Knowledge	Conditional knowledge	7	0.81	0.84	0.52
Metacognitive Regulation	Planning	10	0.88	0.90	0.57
Metacognitive Regulation	Monitoring	9	0.86	0.88	0.55
Metacognitive Regulation	Evaluating	7	0.82	0.85	0.53
Overall scale	—	52	0.95	0.96	0.58

**Table 3** presents the reliability and validity indices for all MAI components, confirming that the instrument meets international standards for use in metacognition and PBL research.

Cronbach's Alpha ( $\alpha$ ) values of 0.81–0.88 for the subscales indicate good reliability. Composite Reliability (CR) values are all  $> 0.80$ , ensuring internal consistency. AVE values are all  $\geq 0.50$ , ensuring convergent validity according to Hair et al. (2019) criteria. The entire scale has  $\alpha = 0.95$  and  $CR = 0.96$ , making it suitable for use in the PBL study.

Independent-samples t-tests (Table 4) revealed significant baseline differences between the experimental and control groups on several components ( $p < .05$ ). Therefore, analysis of covariance (ANCOVA) was employed in subsequent analyses to control for preexisting differences.

**Table 4. Pre-test Comparison Between Groups**

Component	Control (M ± SD)	Experimental (M ± SD)	t	p
Declarative knowledge	3.21 ± 0.42	3.34 ± 0.45	-2.01	.046
Procedural knowledge	3.18 ± 0.40	3.31 ± 0.43	-2.15	.034
Conditional knowledge	3.25 ± 0.41	3.36 ± 0.44	-1.87	.064
Planning	3.10 ± 0.43	3.28 ± 0.46	-2.45	.016
Monitoring	3.14 ± 0.39	3.29 ± 0.42	-2.27	.025
Evaluating	3.12 ± 0.41	3.27 ± 0.44	-2.18	.029

**RQ3.** To address RQ3, ANCOVA was conducted to examine whether students' metacognitive skills improved after participating in PBL compared to traditional instruction.

The results showed a significant effect of instructional method on overall metacognitive performance,  $F(1, 125) = 58.42$ ,  $p < .001$ , partial  $\eta^2 = .32$ . After controlling for pre-test scores, the adjusted mean of the PBL group ( $M = 4.30$ ) was substantially higher than that of the control group ( $M = 3.79$ ), indicating a strong positive effect of PBL (Tables 5 and 6).

**Table 5. ANCOVA Results for Overall Metacognitive Scores**

Source	df	F	p	Partial $\eta^2$
Group (Instruction)	1	58.42	< .001	.32
Pre-test (Covariate)	1	122.35	< .001	.47
Error	125	-	-	-

The adjusted means showed that the experimental (PBL) group ( $M_{adj} = 4.30$ ,  $SE = 0.016$ , 95% CI [4.27, 4.33]) significantly outperformed the control group ( $M_{adj} = 3.79$ ,  $SE = 0.016$ , 95% CI [3.76, 3.82]), demonstrating a substantial positive effect of PBL on students' metacognitive development. (Table 6)

**Table 6. Adjusted Means for Post-test MAI Scores**

Group	Adjusted Mean	SE	95% CI
Control	3.79	0.016	[3.76, 3.82]
Experimental (PBL)	4.30	0.016	[4.27, 4.33]

At the component level, significant effects were observed in all dimensions. Metacognitive regulation showed stronger effects than metacognitive knowledge, with the largest effects found for planning ( $\eta^2 = .21$ ) and evaluation ( $\eta^2 = .22$ ). These findings indicate that PBL is particularly effective in enhancing higher-order regulatory processes in students.

**RQ1.** To address RQ1, Pearson's correlation analysis was conducted to examine the relationship between metacognitive regulation and problem-solving performance.

As shown in Table 7, all correlations were statistically significant ( $p < .01$ ), ranging from moderate to strong ( $r = .46-.62$ ). Planning was most strongly associated with problem identification ( $r = .52$ ), whereas monitoring and evaluation were more strongly related to the execution and evaluation stages ( $r = .57-.62$ ).

**Table 7. Correlations Between Metacognitive Regulation and Problem-Solving Components**

	PI	PP	EX	EV
Planning	.52	.49	.46	.51
Monitoring	.48	.55	.60	.58
Evaluating	.50	.53	.57	.62

(Note: PI = Problem Identification; PP = Planning Procedure; EX = Execution; EV = Evaluation)

These findings indicate that metacognitive regulation is closely aligned with the different phases of problem-solving.

Students' metacognitive regulation skills were significantly and meaningfully correlated with their problem-solving performance across all stages.

**RQ2.** To further address RQ2, multiple regression analyses were conducted to examine the predictive relationships between metacognitive processes and specific problem-solving stages.

The results indicate that planning significantly predicted problem identification ( $\beta = .45, p < .001$ ), monitoring predicted execution ( $\beta = .52, p < .001$ ), and evaluation predicted solution evaluation ( $\beta = .55, p < 0.001$ ).

These findings demonstrate a structured alignment between metacognitive regulation and problem-solving.

Metacognitive processes show significant predictive relationships with the corresponding problem-solving stages, supporting a functional link between regulation and cognitive performance.

The CFA results (Table 8) indicated an excellent model fit (CFI = 0.992, TLI = 0.991, RMSEA = 0.021), confirming the validity of the measurement model used in this study.

**Table 8. CFA Model Fit Indices**

Index	Threshold	Result
CMIN/df	< 2.00	1.142
GFI	> 0.90	0.925
CFI	> 0.90	0.992
TLI	> 0.90	0.991
RMSEA	< 0.08	0.021
PCLOSE	> 0.05	0.997

These indices confirm that the measurement model fits the data well, supporting the validity of the adapted MAI for the PBL context.

## DISCUSSION

This study examined the effects of problem-based learning (PBL) on students' metacognitive skills and explored the relationship between metacognition and problem-solving. Overall, the findings provide consistent evidence that PBL significantly enhances students' metacognitive development and supports their engagement in problem-solving.

Specifically, the results indicate that (i) PBL leads to significant improvements in both metacognitive knowledge and regulation (RQ3); (ii) metacognitive regulation is moderately to strongly associated with problem-solving performance (RQ1); and (iii) metacognitive processes demonstrate predictive relationships with specific stages of problem solving (RQ2).

The findings revealed that students exposed to PBL significantly outperformed those in the traditional instruction group in terms of overall metacognitive skills, even after controlling for baseline differences. This supports the growing body of research suggesting that PBL environments promote active engagement, self-regulation and reflective thinking.

Importantly, the effect sizes observed in this study were moderate to large, indicating that PBL is not only statistically effective but also educationally meaningful. These findings align with prior research demonstrating that learner-centered instructional approaches foster metacognitive awareness by requiring students to plan, monitor, and evaluate their learning processes.

A key contribution of this study is the differentiation between metacognitive knowledge and regulation. While improvements were observed across all components, metacognitive regulation—particularly planning and evaluation—showed the strongest effects. This suggests that PBL is especially effective in supporting higher-order regulatory processes such as goal setting and reflective judgment.

This finding can be explained by the inherent structure of PBL, which places students in situations that require them to define problems, generate strategies, and continuously evaluate their progress. Such iterative engagement naturally activates metacognitive regulation processes, thereby reinforcing their development over time.

Correlation analysis revealed moderate to strong relationships between metacognitive regulation and problem-solving performance. In particular, planning was strongly associated with problem identification, whereas monitoring and evaluation were more closely linked to the execution and evaluation stages.

These findings support the theoretical perspective that metacognition is a central mechanism in effective problem solving. Rather than functioning as a separate cognitive process, metacognition appears to be deeply embedded within problem-solving activities, guiding students' decisions and actions at every stage.

Importantly, the strength of these relationships suggests that students who can better regulate their thinking are also more effective at navigating complex problem-solving tasks. This reinforces the view that metacognitive skills are not merely supportive but foundational for successful learning in STEM contexts.

Beyond correlational relationships, regression analyses provide evidence of directional associations between metacognitive processes and the problem-solving stages. Specifically, planning predicted problem identification, monitoring predicted execution, and evaluation predicted solution evaluation.

These findings extend existing research by demonstrating how specific metacognitive components are functionally aligned with the corresponding stages of problem-solving. This alignment suggests a structured interplay between metacognition and cognition, wherein regulatory processes actively shape students' engagement with tasks.

However, it is important to note that while these results indicate directional relationships, they do not fully establish reciprocal causality. The interactions between metacognition and problem-solving are likely dynamic and iterative, with each influencing the other over time. Future research employing longitudinal or structural equation modeling approaches may provide deeper insights into these mechanisms.

This study contributes to the literature in a number of ways.

First, it provides empirical support for integrating metacognitive theory with problem-based learning frameworks. By demonstrating that PBL enhances both metacognitive knowledge and regulation, the findings reinforce constructivist perspectives that emphasize active, self-directed learning.

Second, this study advances the understanding of the relationship between metacognition and problem solving by identifying specific links between regulatory processes and problem-solving stages. This moves beyond general associations and offers a more nuanced, process-oriented perspective.

Third, the findings suggest that metacognitive regulation can be conceptualized as a mediating mechanism through which instructional approaches, such as PBL, influence learning outcomes. This provides a potential theoretical bridge between instructional design and cognitive development.

From a pedagogical perspective, the findings highlight the importance of designing learning environments that actively promote metacognitive engagement.

Teachers should incorporate instructional strategies that encourage students to plan their approach to tasks, monitor their progress, and reflect on their results. PBL provides a natural context for such practices, but its effectiveness depends on careful implementation, including appropriate scaffolding and guidance.

In particular, explicit support for metacognitive processes, such as prompting students to articulate their reasoning or evaluate their strategies, may further enhance the benefits of PBL. This suggests that integrating metacognitive scaffolding into PBL environments is a promising direction for instructional innovation.

**Limitations and Future Research:** Despite its contributions, this study has some limitations.

First, the quasi-experimental design and the presence of baseline differences between groups may limit the strength of causal inferences, although the use of ANCOVA helps to mitigate this concern.

Second, reliance on self-report measures for metacognition may introduce bias, as students' perceptions of their thinking processes may not fully reflect their actual behaviors.

Third, the study was conducted in a specific educational context, which may limit the generalizability of the findings.

Future research should employ longitudinal designs, multi-method assessments, and more diverse samples to further validate and extend these findings. Additionally, the use of structural equation modeling could provide deeper insights into the reciprocal relationships between metacognition and problem-solving.

## CONCLUSION

This study provides empirical evidence that problem-based learning (PBL) significantly enhances secondary students' metacognitive development and strengthens their relationship with problem-solving performance. After controlling for baseline differences, students engaged in PBL demonstrated meaningful improvements in both metacognitive knowledge and regulation, confirming the effectiveness of learner-centered instructional approaches (RQ3).

The findings further revealed moderate to strong associations between metacognitive regulation and key stages of problem-solving, highlighting the integral role of planning, monitoring, and evaluation in guiding students' cognitive processes (RQ1). In addition, regression analyses suggest that specific metacognitive components predict the corresponding problem-solving stages, offering insights into the functional alignment between these constructs (RQ2).

Taken together, these results position metacognition not only as an outcome of PBL but also as a central mechanism through which learning is regulated and transferred to new contexts. While causal interpretations should be made cautiously, this study contributes to a more nuanced understanding of how instructional design can foster self-regulated, adaptive learners in secondary science education.

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**Data Availability Statement:** The datasets generated and analyzed in this study are available from the corresponding author upon reasonable request.

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