



The effects of e-problem-based learning on students' geometry problem-solving performance across Polya's stages

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Abstract

This study addresses persistent difficulties in students' geometry problem-solving, particularly in coordinating representations and applying structured reasoning. Prior research has shown the potential of problem-based learning (PBL) and digital tools; however, limited evidence exists regarding how technology-enhanced PBL supports students' engagement across Polya's problem-solving stages. To examine this issue, a quasi-experimental pretest–posttest control group design was employed involving two intact undergraduate geometry classes. The experimental group was taught using e-Problem-Based Learning (e-PBL), while the control group received conventional instruction. Students' performance was measured using a Polya-based problem-solving test. Data were analyzed using descriptive statistics, assumption testing, and an independent samples t-test. The results showed that the experimental group outperformed the control group ($M = 70.74$ vs. 65.07), with a statistically significant difference ($p < .001$) and a large effect size ($d = 1.16$). Performance gains were observed across all four stages of Polya's framework, particularly in the planning and reflection stages. These findings suggest that e-PBL is associated with improved mathematical problem-solving performance by supporting structured reasoning and reflective thinking. The research emphasizes the necessity of integrating digital scaffolding and collaborative inquiry in geometry instruction.

Keywords: e-problem-based learning; geometry learning; mathematical problem solving; multimodal representations; Polya's heuristic stages

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Introduction

Mathematical problem solving remains a central aim of mathematics education because it requires the integration of conceptual understanding, strategic reasoning, and metacognitive regulation. Contemporary research indicates that success in mathematical problem-solving, particularly in word problems and geometry, depends on learners' ability to coordinate reading comprehension, numerical reasoning, and representational fluency (Fuchs et al., 2016; Tessema et al., 2024). These processes are jointly shaped by working memory, processing speed, and fluid reasoning, which regulate how learners interpret problem information and monitor solution strategies (Siegler & Braithwaite, 2017). Accordingly, mathematical vocabulary and domain-specific reading comprehension function as critical predictors of performance when learners extract quantitative relations from textual and visual representations (Baker et al., 2017; Mahlaba & Mudaly, 2022; Vilenius-Tuohimaa et al., 2008).

Despite this theoretical understanding, many learners experience persistent difficulties in problem-solving that cannot be attributed solely to procedural weakness. Qualitative studies suggest that these difficulties often arise from learning obstacles that impede the interpretation of problems, the construction of representations, and planning (Hendriyanto et al., 2024). Such obstacles include ontogenic constraints related to cognitive readiness, epistemological limitations in conceptual understanding, and didactical issues arising from instruction that prioritizes mechanical procedures over conceptual coherence (Wahyuni et al., 2025). These obstacles tend to emerge during the early phases of problem solving and continue to affect subsequent stages, undermining solution accuracy and reflective evaluation.

These challenges are particularly salient in geometry, a domain that demands intensive coordination of diagrams, spatial relations, symbolic expressions, and verbal descriptions. Geometry problem-solving requires learners to translate heterogeneous representations into consistent mathematical structures. Research on multimodal problem solving demonstrates that misalignment between visual and verbal information increases cognitive load and fragments reasoning, leading to unstable solution pathways (Jian et al., 2023; Sachan et al., 2020; Zhang et al., 2018). When representational construction remains incomplete, learners often rely on superficial cues, resulting in solutions that lack conceptual robustness (Wahyuni et al., 2025).

This pattern aligns closely with Polya's framework, which conceptualizes mathematical problem solving as a sequence of understanding the problem, devising a plan, carrying out the plan, and reflecting on the outcome (Acuña, 2014; Daulay & Ruhaimah, 2019; Zuckerman & Polya, 1966). Empirical evidence confirms that strong engagement during the understanding and planning stages is closely associated with successful geometry problem solving, whereas weaknesses at these stages frequently propagate through execution and reflection (Türkoğlu & Yalçınalp, 2024). Didactical analyses further reveal that epistemological and didactical obstacles often arise when learners apply formal structures prematurely, without grounding them in meaningful representations (Wahyuni et al., 2025).

Advances in digital learning environments have created new opportunities to support and examine these cognitive processes. Digital platforms increasingly incorporate scaffolds, multimodal representations, and adaptive feedback that extend mathematical exploration

beyond static instructional formats (Mao et al., 2025; Saat et al., 2024). Studies on dynamic geometry systems and mobile-based STEM environments report improvements in conceptual exploration and strategic experimentation, while learning analytics approaches provide detailed insights into learners' problem-solving trajectories (Siregar, 2025; Tassilova et al., 2025; Yang et al., 2025).

Within this context, electronic Problem-Based Learning integrates the epistemic structure of problem-based inquiry with web-based affordances to promote sustained engagement with complex problems. Empirical studies suggest that e-PBL supports deeper reasoning and self-directed inquiry through authentic problem scenarios (Phumeechanya & Wannapiroon, 2014; Wagino et al., 2024; Yu & Zin, 2023). However, existing evidence also indicates that the effects of PBL on achievement are often mediated by affective and social variables rather than exerting a direct influence on performance (Amiruddin et al., 2021; Wardi et al., 2023). This observation highlights the importance of investigating how learners cognitively engage with problem-solving tasks within e-PBL environments.

Technology-enhanced PBL environments that incorporate dynamic visualization tools offer additional instructional potential. Comparative studies show that PBL supported by GeoGebra leads to higher levels of mathematical representation ability than alternative instructional approaches, particularly among analytically oriented learners (Amalia et al., 2020). More recent research demonstrates that immersive technologies such as augmented reality further enhance problem-solving in spatial geometry by supporting visualization and reducing abstraction barriers (Maulana et al., 2025). When aligned with structured thinking models, these technologies facilitate meaningful exploration and reflective reasoning.

Despite extensive research on problem-based learning and digital environments, limited studies have explicitly examined how technology-enhanced PBL influences learners' engagement across the full sequence of Polya's problem-solving stages. Existing studies tend to focus on achievement, representational outcomes, or affective variables in isolation, leaving stage-specific cognitive processes such as problem understanding and planning insufficiently examined (Kirabo et al., 2024). In particular, the role of digital scaffolding in mitigating epistemological and didactical obstacles during these early phases remains underexplored (Wahyuni et al., 2025).

This gap is especially salient in the Indonesian context, where international assessments consistently indicate low performance in mathematical literacy and geometry reasoning. Although the Merdeka Curriculum promotes inquiry-oriented learning, classroom practices often lack structured digital problem-based designs that systematically support reasoning across problem-solving stages (Udil et al., 2025; Wahyuni et al., 2025).

Accordingly, this study examines how e-PBL influences students' geometry problem-solving performance through the lens of Polya's framework using a quasi-experimental design. By analyzing learning gains across all four problem-solving stages and integrating digital scaffolds and multimodal representations, this study reconceptualizes Polya's heuristic stages as digitally mediated cognitive trajectories rather than static procedural steps, while also testing the effect of e-PBL on students' performance across Polya's four stages (Kirabo et al., 2024). This study tests the following hypothesis:

H₀: There is no significant difference in mathematical problem-solving performance between students taught using e-PBL and those receiving conventional instruction.

H₁: Students in an e-PBL environment demonstrate significantly higher problem-solving performance across all four stages of Polya's framework compared to those in a conventional instruction group.

Methods

Research design

This study employed a quasi-experimental pretest–posttest control group design to examine the effectiveness of electronic Problem-Based Learning in enhancing students' Polya-based mathematical problem-solving performance in geometry. Random assignment was not feasible due to institutional scheduling constraints that required students to remain in intact classes; therefore, a quasi-experimental approach was adopted as a methodologically appropriate alternative for evaluating instructional effects in authentic educational settings (Campbell & Stanley, 2015).

The experimental group engaged in learning activities structured through the e-PBL design and delivered via a learning management system, whereas the control group received conventional instruction consistent with departmental practice. This design allowed for systematic comparison of learning gains between groups while accounting for baseline differences through pretest measurement, an approach commonly used in technology-enhanced problem-based learning research (Choi et al., 2022).

The selection of intact classes was based on institutional scheduling policies that prohibit random reassignment of students across classes. Both classes were taught by the same instructor, used the same syllabus, and were scheduled within the same academic period to minimize instructor and temporal bias. Pretest analysis was conducted to verify baseline equivalence between groups.

Research setting and timeline

The study was conducted in the Mathematics Education Department of UIN Siber Syekh Nurjati Cirebon and followed established institutional research procedures. The research process progressed sequentially, beginning with proposal refinement and a focused review of relevant literature, followed by the development of instructional materials and assessment instruments.

Prior to implementation, the e-PBL lesson plan and problem-solving instruments were validated by experts to ensure content accuracy and instructional coherence. The intervention was carried out during the geometry instructional unit, with experimental and control groups taught concurrently under comparable conditions. Data were collected throughout the instructional period through pretests and posttests, student response questionnaires, and documentation of learning activities. The study concluded with data analysis and interpretation,

maintaining continuity and methodological transparency across all research stages (Creswell & Creswell, 2017).

Population and sample

The population comprised undergraduate students enrolled in the Geometry course within the Mathematics Education program. Purposive sampling was used to select participants, consistent with educational research practices that require the use of intact classes. Two parallel classes were assigned as the experimental and control groups.

The classes were comparable in academic level, course content, and instructional schedule. A pretest was administered prior to the intervention to establish baseline equivalence in mathematical problem-solving performance. The use of intact classes combined with verification of initial equivalence aligns with quasi-experimental standards and supports the internal validity of the study (Creswell & Creswell, 2017).

Research variables

The independent variable in this study was the e-Problem-Based Learning model, while the dependent variable was students' mathematical problem-solving performance. The e-PBL intervention was grounded in social constructivist theory and digital problem-based learning principles, emphasizing collaborative inquiry, reflective reasoning, and mediated learning through online tools.

Problem-solving performance was operationalized using Polya's four-stage framework: understanding the problem, devising a plan, carrying out the plan, and evaluating the solution. This framework remains a widely accepted theoretical model and is supported by recent empirical findings indicating that effective problem solvers allocate substantial cognitive effort to the understanding and planning stages (Türkoğlu & Yalçınalp, 2024). Accordingly, Polya's framework informed both the development of the instrument and the analysis of the data.

Table 1. Comparison of instructional design

Aspect	e-PBL (Experimental)	Conventional (Control)
Learning approach	Problem-based, inquiry-driven	Lecture-based
Technology use	LMS, GeoGebra, digital worksheets	None/minimal
Collaboration	Online group discussion	Individual work
Scaffolding	Structured prompts, reflection tasks	Limited guidance
Problem type	Authentic, open-ended problems	Routine exercises

The e-PBL intervention was implemented through a structured four-phase learning cycle to ensure procedural clarity and instructional consistency. In the first phase (problem orientation), students were introduced to contextual geometry problems presented through a Learning Management System (LMS), where problem scenarios were designed to stimulate initial interpretation and questioning. In the second phase (collaborative investigation), students worked in small groups to explore problem representations using GeoGebra and digital worksheets, enabling them to construct and manipulate visual models while identifying relevant mathematical relationships. In the third phase (discussion and solution development), each

group articulated their reasoning, compared alternative strategies, and refined their solutions through asynchronous online discussions facilitated by the LMS discussion forum. In the final phase (reflection and evaluation), students engaged in guided reflection activities using structured prompts that encouraged them to review their solution processes, evaluate correctness, and consider alternative approaches.

Throughout these phases, instructional scaffolding was systematically embedded in the form of guiding questions, stepwise prompts, and feedback mechanisms provided within the LMS environment. The integration of GeoGebra supported dynamic visualization, while digital worksheets were designed to align with Polya's four problem-solving stages, ensuring that students' cognitive processes were consistently directed toward understanding, planning, execution, and reflection.

Data collection techniques and instruments

Data were collected using three primary instruments: a Polya-based problem-solving test, expert validation sheets for the e-PBL lesson plan, and a student response questionnaire. The problem-solving test consisted of open-ended items designed to elicit students' reasoning processes across all four stages of Polya's model (Acuña, 2014). The test was administered before and after the intervention to measure changes in performance.

To ensure instructional quality, the e-PBL lesson plan was evaluated by experts in mathematics education, who assessed content relevance, clarity, instructional structure, and pedagogical alignment. Their judgments were quantified using the Content Validity Index procedure, which is widely applied in instructional design research (Rahmat et al., 2024; Almanasreh et al., 2019). Additionally, students in the experimental group completed a Likert-scale questionnaire assessing their learning experience, including the clarity of problem scenarios, the usefulness of digital tools, and the quality of collaborative engagement. Together, these instruments captured both outcome-based and process-oriented dimensions of the intervention.

Instrument validity and reliability

Validity was established through expert judgment to confirm that the lesson plan and test items adequately represented the intended constructs. Experts evaluated each component using structured criteria aligned with the standards of content validity. Content Validity Index calculations were then used to determine agreement levels, following the procedures reported by Castro and Tumibay (2021).

Reliability of the problem-solving test was examined through internal consistency analysis to ensure stable measurement across Polya's stages. This validation process was completed prior to implementation, providing assurance that the instruments were both conceptually sound and empirically reliable. The Content Validity Index (CVI) for the problem-solving instrument was 0.89, indicating high content validity. The reliability analysis yielded a Cronbach's alpha of 0.87, demonstrating strong internal consistency.

Data analysis techniques

Data analysis began with assumption testing to determine the suitability of parametric procedures. Normality was examined using Kolmogorov-Smirnov and Shapiro-Wilk tests, while homogeneity of variance was assessed using Levene's Test.

To evaluate the effectiveness of the e-PBL intervention, an independent samples t-test was conducted to compare posttest scores between the experimental and control groups, following common quasi-experimental practices in digital learning research (Quarder et al., 2025). Descriptive statistics were used to examine performance patterns across Polya's four problem-solving stages, enabling a more detailed interpretation of students' cognitive processes. Responses from the student questionnaire were also analyzed descriptively to capture perceptions of digital scaffolding and collaborative learning features.

Pretest scores were examined prior to inferential analysis to verify baseline equivalence between groups. This procedure supports the internal validity of posttest comparisons in quasi-experimental designs where intact classes are retained and instructional effects are interpreted relative to initial performance levels.

Results

The data in this study were obtained from an essay-based mathematical problem-solving test administered to two groups: an experimental group and a control group.

Table 2. Descriptive statistics

Statistics	Experimental Group (MPS)	Control Group (MPS)
N	37	37
Range	20	20
Minimum	59	48
Maximum	79	68
Mean	70.74	65.07
Std. Deviation	4.801	4.976
Variance	23.046	24.764

Table 2 presents the descriptive statistics of students' mathematical problem-solving performance in the experimental and control groups. The experimental group obtained a higher mean score ($M = 70.74$) than the control group ($M = 65.07$), yielding a mean difference of 5.67 points in favor of students who participated in the e-PBL intervention. This difference indicates a notable performance advantage associated with the instructional treatment. Importantly, both groups exhibited comparable levels of score dispersion, as reflected in similar standard deviations ($SD = 4.801$ for the experimental group and $SD = 4.976$ for the control group) and variances (23.046 and 24.764, respectively). The equivalence in variability suggests that the observed mean difference was not attributable to extreme scores or uneven distribution, but rather reflects a consistent shift in overall performance. In addition, identical score ranges and overlapping minimum and maximum values indicate that the intervention influenced general performance trends across students rather than benefiting only a limited subset of high-achieving individuals.

Table 3. Pretest comparison

Group	N	Mean	SD	t	Sig. (2-tailed)
Experimental	37	59.30	4.484	0.478	0.643
Control	37	60.05	4.636		

The results indicate no significant difference between groups at pretest ($t = 0.478$, $p = 0.634$), confirming baseline equivalence and supporting the validity of subsequent posttest comparisons.

Table 4. Achievement of Problem-Solving Indicators

Polya's Indicators	Experimental	Control	Gain (E – C)
Understanding the problem	97%	90%	+7%
Devising a plan	98%	82%	+16%
Carrying out the plan	92%	87%	+5%
Looking back	88%	60%	+28%

A stage-based examination of Polya's problem-solving indicators reveals clear differences in how students organized and enacted their problem-solving processes. As shown in Table 3, performance across the four stages consistently favored the experimental group, particularly in stages requiring conceptual understanding and strategic decision making. This pattern suggests qualitative differences in problem approach rather than superficial score variation.

The contrast is evident at the Understanding the Problem stage, where the experimental group achieved 97% compared with 90% in the control group, indicating stronger initial comprehension of problem conditions. The gap widened substantially at the Devising a Plan stage. Here, the experimental group reached 98%, while the control group attained 82%, producing a 16 percentage-point difference. This finding indicates that students engaged in the e-PBL environment were more capable of organizing relevant information and formulating coherent solution strategies before execution.

Differences remained evident in the later stages of the problem-solving sequence, though their magnitude varied. During the *Carrying Out the Plan* phase, performance levels between groups were closer, with a 5 percentage-point difference between the experimental group at 92% and the control group at 87%. A markedly different pattern emerged in the *Looking Back* stage. The experimental group recorded an attainment rate of 88%, whereas the control group reached only 60%, yielding a substantial 28 percentage-point gap. This contrast highlights a stronger capacity for solution evaluation, error checking, and reflective reasoning among students in the experimental condition.

Overall, the distribution of results across stages indicates that the e-PBL intervention supported a more integrated and coherent problem-solving process. Gains were most pronounced in the planning and reflection stages, which are closely associated with strategic reasoning and metacognitive regulation. The consistently higher attainment of the experimental group across all Polya stages reinforces the interpretation that the observed advantages reflect differences in problem-solving quality rather than isolated procedural gains.

Table 5. Normality test results

Group	Kolmogorov–Smirnov			Shapiro–Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
MPS Experimental	0.136	37	0.200*	0.961	37	0.397
MPS Control	0.087	37	0.200*	0.983	37	0.926

*Lilliefors significance correction.

Table 6. Homogeneity test (Levene's Test)

Levene Statistic	df1	df2	Sig.
0.124	1	72	0.726

Prior to inferential analysis, statistical assumptions were carefully examined to ensure the appropriateness of parametric procedures. As shown in Table 4, the results of the Shapiro–Wilk test indicated that the distribution of mathematical problem-solving scores was normal for both the experimental group ($p = .397$) and the control group ($p = .926$). In addition, Levene's Test for equality of variances (Table 5) yielded a non-significant result ($p = .726$), confirming homogeneity of variance between groups. Taken together, these findings indicate that the data satisfied the assumptions of normality and homogeneity, thereby supporting the use of parametric statistical analyses in subsequent stages of the study.

Table 7. independent samples t-test of mathematical problem-solving skill

Statistic	Value
N (Experimental / Control)	37 / 37
Mean Difference	5.67
Degrees of Freedom (df)	72
Sig. (2-tailed)	< .001
Effect Size (Cohen's d)	1.16
Effect Size Interpretation	Large

Table 7 summarizes the inferential analysis comparing posttest mathematical problem-solving performance between the experimental and control groups, including statistical significance and effect size estimation. To assess the magnitude of the observed difference, Cohen's d was calculated using the pooled standard deviation ($SD_{pooled} \approx 4.89$). The resulting effect size ($d \approx 1.16$) represents a large effect according to established benchmarks in educational research, indicating a substantial separation between group performance distributions. Overall, these findings indicate that the e-PBL intervention was associated with a strong and practically meaningful improvement in students' Polya-based mathematical problem-solving performance in geometry.

Discussion

Building on the stage-based differences reported in Table 4, particularly the pronounced gaps at the stages of devising a plan and looking back, the following discussion interprets these findings in relation to the cognitive, technological, and pedagogical mechanisms underlying students' problem-solving processes.

The findings of this study indicate that e-PBL is associated with a statistically significant improvement in students' mathematical problem-solving performance when examined through Polya's framework. Gains across all four stages suggest that e-PBL may support problem solving as an integrated cognitive process rather than a sequence of isolated procedures. This pattern aligns with contemporary views that conceptualize problem-solving as a process involving interpretation, strategic planning, execution, and reflective regulation, sustained by cognitive engagement (Acuña, 2014; Maulana et al., 2025; Türkoğlu & Yalçınalp, 2024). The strongest improvements occurred during the understanding and planning stages, which are widely recognized as the most cognitively demanding and determinative of solution quality (Wahyuni et al., 2025). Difficulties at these stages often propagate into later phases, resulting in flawed execution and superficial evaluation (Fuchs et al., 2016; Mao et al., 2025). The present findings extend this literature by suggesting that e-PBL environments may help mitigate such early-stage difficulties, particularly those associated with epistemological and didactical obstacles during problem interpretation and representation construction (Wahyuni et al., 2025). This stage-specific pattern provides an initial indication that the observed performance differences are rooted in how students engage with problems from the outset, rather than in procedural fluency alone. However, these interpretations should be considered with caution, as alternative explanations such as increased student engagement due to the novelty of digital tools or heightened attention during the intervention period (Hawthorne effect) may also have influenced the observed differences. In addition, although efforts were made to control instructional conditions, subtle variations in interaction dynamics or student responsiveness cannot be entirely excluded.

The effectiveness of e-PBL can be further explained by the affordances of digital tools embedded within the learning environment. Dynamic geometry environments and multimodal representations reduce cognitive load by externalizing relationships that are difficult to infer from static diagrams, enabling learners to manipulate objects, explore invariants, and test conjectures iteratively (Adelabu et al., 2019; Jian et al., 2023; Ng & Sinclair, 2015). Learning analytics studies indicate that successful problem solvers in technology-supported environments allocate greater attention to problem statements and engage in iterative reading and revisiting behaviors, particularly when visualization scaffolds comprehension (Kirabo et al., 2024; Zhang et al., 2018). These mechanisms may help explain the experimental group's superior performance during the execution and evaluation stages. In this sense, digital affordances function not as add-ons, but as integral supports that reshape how cognitive resources are distributed across problem-solving phases.

Collaboration and reflection, which are core features of e-PBL, appear to have contributed to the observed learning gains. e-PBL requires learners to articulate ideas, justify strategies, and

negotiate meaning, processes known to deepen conceptual understanding and expose misconceptions (Barrows, 1996; Hung, 2011). When enacted in digital environments, these interactions become more visible and traceable, supporting systematic reflection and strategic revision (Hu & Tseng, 2016; Kirabo et al., 2024). Prior studies suggest that digitally scaffolded collaboration fosters strategic reasoning and creative problem solving, especially in complex or unfamiliar tasks (Chen et al., 2008; Doo et al., 2020). This mechanism is consistent with students' responses in the present study, which emphasized the clarity of digital prompts, structured group tasks, and opportunities for iterative revision. Such interactional patterns help clarify why improvements were not confined to execution, but extended to earlier planning and later evaluative stages. It is also important to acknowledge that these findings are context-dependent, and the observed advantages may partially reflect students' adaptation to a more structured and interactive learning environment rather than the instructional model alone.

The particularly strong gains observed in the looking back stage warrant further attention. Reflection has long been recognized as a crucial mechanism for consolidating learning and facilitating transfer (Breda et al., 2017; Daulay & Ruhaimah, 2019). Contemporary learning science reinforces this view, identifying reflective evaluation and productive struggle as key predictors of durable learning and adaptive expertise (Amalia et al., 2020; Moreno & Mayer, 2007). The digital features of e-PBL **may support** these processes by enabling learners to revisit prior solutions, compare alternative strategies, and re-evaluate assumptions, thereby strengthening metacognitive awareness and strategic adaptability (Hu & Tseng, 2016; Munawaroh et al., 2022). The prominence of gains at this stage suggests that e-PBL creates conditions in which reflection becomes a natural continuation of problem solving rather than an optional afterthought.

These findings are particularly relevant in geometry education, where students often struggle to interpret three-dimensional structures through two-dimensional representations. Limitations in spatial visualization frequently lead to fragmented reasoning and inaccurate solution construction (Tessema et al., 2024). Both physical and digital manipulatives have been shown to enhance conceptual clarity by supporting problem decomposition and representational coherence (Budakoğlu et al., 2023; Sugianto et al., 2025). The integration of interactive visual elements within the e-PBL design is likely associated with the experimental group's improved geometric intuition, enabling more consistent alignment between conceptual structures and procedural steps. This alignment offers a plausible explanation for the coherence observed across Polya stages in the experimental group's performance.

Beyond cognitive mechanisms, motivational and affective factors also appear to have reinforced the observed learning gains. Technology-supported collaborative environments have been shown to enhance engagement, persistence, and confidence, which indirectly support mathematical performance (Fuchs et al., 2016; Mao et al., 2025). Qualitative responses in the present study suggest that students perceived e-PBL as meaningful and interactive, fostering sustained engagement with challenging geometry tasks (Eilouti, 2018). Such affective engagement amplifies the cognitive benefits of inquiry-oriented learning by encouraging productive struggle and fostering a deeper sense of meaning (Kotsis, 2025; Sengupta-Irving &

Enyedy, 2015). These affective dimensions may have interacted with cognitive supports to sustain students' involvement across multiple problem-solving cycles.

The magnitude of the observed effect size should be interpreted within the specific instructional and contextual conditions of this study. The large effect may reflect the strong alignment between the e-PBL design, the Polya-based assessment framework, and the instructional emphasis on explicit problem-solving stages. Participants were introduced to a learning environment that differed substantially from their prior experiences, which were predominantly characterized by procedure-oriented instruction with limited opportunities for strategic planning and reflection. In such contexts, interventions that explicitly scaffold understanding, representation construction, and reflective evaluation are likely to yield pronounced gains, particularly among learners with limited prior exposure to inquiry-oriented digital learning. Moreover, the relatively focused instructional duration and the close correspondence between learning activities and assessment tasks may have amplified the observed differences. These conditions suggest that while the results provide robust evidence of e-PBL's effectiveness, the magnitude of the effect should be generalized with caution and examined further across longer instructional periods, diverse learner profiles, and varied curricular contexts. This consideration frames the findings as analytically robust while remaining sensitive to contextual boundaries.

Taken together, these findings suggest that e-PBL may serve as a pedagogical approach that can strengthen mathematical problem-solving competence. through the combined effects of digital scaffolding, collaborative inquiry, and structured reflection. Theoretically, the results extend Polya's heuristics into digitally mediated learning contexts by demonstrating how e-PBL supports stage-specific cognitive processes and reduces learning obstacles at their point of origin. Pedagogically, the study provides evidence that well-designed e-PBL environments offer a viable pathway for fostering strategic, reflective, and conceptually grounded problem solving in geometry, particularly in contexts where traditional instruction has struggled to address persistent difficulties. In this way, the discussion moves beyond performance outcomes to illuminate the processes through which such outcomes are realized.

In the Indonesian context, where the Merdeka Curriculum emphasizes inquiry-based learning, the findings suggest that e-PBL may serve as a practical framework for implementing structured problem-solving instruction. However, challenges such as limited digital infrastructure and varying teacher readiness should be considered when scaling this approach.

This study is subject to several limitations. First, the quasi-experimental design without random assignment limits causal inference. Although baseline equivalence was established, unmeasured variables may still have influenced the results. Second, the study was conducted within a single institutional context, which may limit generalizability. Third, potential instructor and novelty effects (e.g., increased engagement due to new technology) cannot be fully ruled out. Finally, the study did not examine long-term retention of problem-solving skills.

Conclusion

Building on the patterns discussed above, this study suggests that e-Problem-Based Learning (e-PBL) constitutes an effective instructional approach for enhancing students' mathematical problem-solving performance in geometry when examined through Polya's problem-solving framework. The consistent gains observed across all four stages, with particularly pronounced improvements in understanding, planning, and reflective evaluation, suggest that e-PBL supports problem solving as a coherent cognitive trajectory rather than a collection of disconnected procedural actions. These findings extend Polya's heuristics into digitally mediated learning contexts by illustrating how digital scaffolding, multimodal representations, and collaborative inquiry help stabilize stage-specific cognitive processes and reduce learning obstacles that frequently emerge during early problem interpretation and planning. Within this configuration, e-PBL operates less as a supplementary instructional technique and more as a design framework that reshapes learners' cognitive engagement with mathematical problems.

From an applied perspective, the results indicate that effective implementation of e-PBL in geometry instruction requires deliberate attention to representation construction, strategic planning, and reflective evaluation, supported by digital visualization tools and structured collaborative activities. For teachers and curriculum developers, this underscores the importance of shifting away from predominantly procedure-oriented instruction toward inquiry designs that foreground reasoning, discussion, and revision. At the policy level, the findings provide empirical support for integrating e-PBL into inquiry-oriented mathematics curricula as a means of fostering more robust and transferable problem-solving competence. Future research is therefore warranted to examine the longitudinal effects of e-PBL across diverse learner profiles, mathematical domains, and instructional durations, as well as to explore how different forms of digital scaffolding interact with learners' prior knowledge and cognitive characteristics. Future research should employ randomized controlled designs to establish stronger causal inference, examine long-term retention effects, and investigate how learner characteristics such as prior knowledge and spatial ability moderate the effectiveness of e-PBL.

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Declarations

Conflicts of Interest : The authors declare that there is no conflict of interest associated with the publication of this manuscript. The authors also affirm that all ethical considerations have been duly observed, including adherence to standards regarding plagiarism, research

- misconduct, data fabrication or falsification, duplicate publication or submission, and unnecessary redundancies.
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