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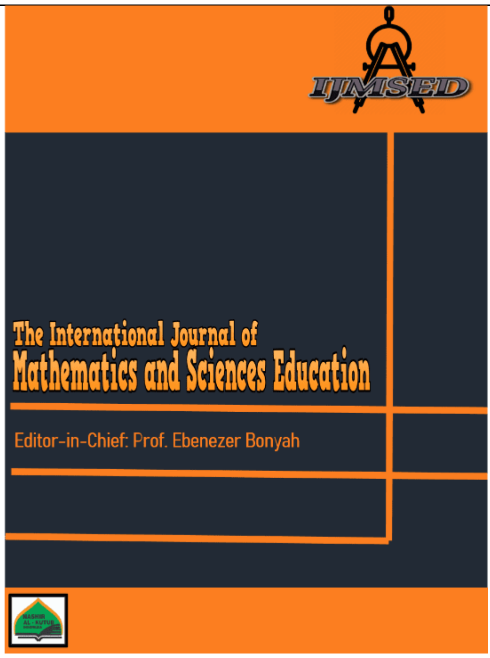

Self-regulated learning and critical thinking in socio-emotionally differentiated problem-based learning: A mixed-methods study in Indonesian junior secondary mathematics

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Self-regulated learning and critical thinking in socio-emotionally differentiated problem-based learning: A mixed-methods study in Indonesian junior secondary mathematics

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Abstract
Mathematical critical thinking remains chronically underdeveloped in Indonesian junior secondary classrooms, yet no study has simultaneously integrated socio-emotional differentiation, Problem-Based Learning (PBL), and structured worksheet scaffolding while examining how self-regulated learning (SRL) predicts critical thinking development. This study addressed that gap by evaluating the quality and effectiveness of a socio-emotionally differentiated PBL model assisted by LKS Ceria, and testing SRL as a predictor of critical thinking performance among eighth-grade students. A quasi-experimental nonequivalent control group design with an explanatory sequential mixed-methods component was implemented at SMPN 4 Juwana (2024/2025 academic year; n = 30 per group). Instruments were validated via Aiken's V (mean V = 0.83) and Cronbach's alpha (α = 0.84–0.87). Data were analyzed using Mann-Whitney U, binomial, Chi-square, and bootstrap regression tests. The model satisfied all three quality criteria: instruments were valid and reliable (planning stage), implementation reached 66% with 77.33% positive student responses (implementation stage), and the experimental class achieved 70% classical mastery — significantly exceeding both the control class (0% mastery; U = 108.5, z = −6.21, p < .001, r = .80) and the criterion proportion (binomial p = .041; χ^2 = 28.46, p < .001). SRL was a significant positive predictor of critical thinking (β = 1.005, SE = 0.313, p = .004, 95% CI [0.387, 1.679]; R^2 = .42), with performance varying systematically by SRL level. This study contributes an empirically validated, socio-emotionally differentiated PBL framework that simultaneously operationalizes scaffolded worksheet support and SRL-based differentiation as a replicable design for developing mathematical critical thinking in junior secondary mathematics.

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1. Introduction

The demands of the 21st century require education systems to develop students who possess critical thinking, creativity, and systematic problem-solving skills — competencies that are increasingly recognized as essential for academic and professional success (Schukajlow & Krug, 2024). In mathematics education, critical thinking is considered a fundamental competency, encompassing the ability to analyze information, evaluate arguments, and draw logical, evidence-based conclusions (Suparman et al., 2021). However, data from the Programme for International Student Assessment (PISA) consistently indicate that Indonesian students' mathematical literacy remains well below the OECD average, revealing a persistent gap between curricular expectations and classroom realities. This gap is compounded by evidence that conventional instructional approaches fail to sufficiently develop students' higher-order thinking skills (Abrenica, 2025). Problem-Based Learning (PBL) has been identified as one of the most effective frameworks for developing mathematical critical thinking (Suparman et al., 2021; Suryawati et al., 2025; Zetriuslita et al., 2023), particularly when combined with differentiated instruction that addresses diverse student needs and has been shown to significantly improve mathematics learning outcomes in Indonesian school contexts (Smale-Jacobse et al., 2020; Pozas & Letzel, 2023; Rahman et al., 2024). Furthermore, self-regulated learning (SRL) has been shown to play a significant mediating role in translating instructional quality into critical thinking performance (Zimmerman, 2000; Liza et al., 2023).

In the specific context of the Pythagorean Theorem at the junior secondary level, several interrelated challenges persist. Preliminary classroom observations at SMPN 4 Juwana revealed that students' critical thinking skills are markedly low: students struggled with basic mathematical operations, misinterpreted word problems, and failed to identify relevant information needed to construct solutions. These difficulties align with the higher-order thinking indicators of analysis, evaluation, and inference identified by Facione (1990) as central to critical thinking competence. Simultaneously, students' self-regulated learning (SRL) was observed to be inadequate — characterized by low initiative, strong peer dependence, and avoidance behaviors. Research consistently confirms that low SRL is associated with poor critical thinking performance in mathematics, and that innovative instructional models can foster learning independence as a key mediating factor in mathematics achievement (Yanwar & Fadila, 2019; Nurintya et al., 2025; Mustikaningsih et al., 2025). Additionally, students' socio-emotional readiness was suboptimal: frequent off-task behavior, low engagement, and emotional disengagement during problem-solving phases were documented through observation. At the junior secondary level specifically, research has demonstrated that structured, problem-oriented learning designs — when integrated with appropriate learning media — can foster self-regulated learning while simultaneously supporting mathematical reasoning development (Isharyadi et al., 2026).

Existing efforts to implement differentiated instruction and socio-emotional learning in Indonesian secondary mathematics classrooms have produced mixed results, with student engagement frequently declining during the problem-solving phase (Fanani et al., 2024). A growing body of research demonstrates that SRL significantly predicts mathematical critical thinking and higher-order thinking performance in problem-based learning environments, with systematic reviews confirming that learning independence consistently influences students' mathematical thinking abilities across diverse instructional contexts (Liza et al., 2023; Yanwar & Fadila, 2019; Nurintya et al., 2025; Nurfaidah et al., 2023). Simultaneously, PBL — especially when supported by structured and differentiated student worksheets (LKPD/LKS) — has been consistently shown to improve learning outcomes and accommodate diverse student readiness levels in junior secondary mathematics (Ayunda et al., 2023; Mulyati, 2023; Abrenica, 2025; Safira & Darmawan, 2025; Muliawanti et al., 2026). However, a critical gap remains in the literature: to date, no study has simultaneously integrated socio-emotional differentiation, PBL, and a structured worksheet medium (LKS Ceria) while explicitly examining how SRL moderates critical thinking development within this integrated framework at the junior secondary level. This study addresses that gap directly.

The need for a more integrative instructional approach is further underscored by diagnostic assessment conducted at the outset of the study, which confirmed 0% classical mastery among all participants, with students demonstrating competence only at the interpretation level of Facione's (1990) critical thinking framework. Observational data corroborated persistently low SRL across the cohort, providing direct empirical justification for the present intervention.

This study proposes an integrative approach that combines Problem-Based Learning, socio-emotionally differentiated instruction, and LKS Ceria as a learning medium. The novelty of this study lies in the simultaneous integration of these approaches to enhance students' mathematical critical thinking skills in relation to their level of self-regulated learning. This integration is expected to promote active engagement, self-regulation, and students' ability to solve problems both independently and collaboratively. Based on the background described above, the following research questions guide this study:

a) How is the quality of the socio-emotionally differentiated PBL model assisted by LKS Ceria in terms of validity, practicality, and effectiveness?
b) To what extent does self-regulated learning significantly predict students' critical thinking skills within the socio-emotionally differentiated PBL model?
c) How do students' critical thinking skills vary based on their levels of self-regulated learning?

2. Methods

2.1 Research Design

This study employed a predominantly quantitative quasi-experimental nonequivalent control group design with supplementary qualitative description (Creswell & Creswell, 2018). The quantitative strand used a pretest-posttest design to examine the effectiveness of the intervention on students' critical thinking skills and to test the predictive effect of SRL on critical thinking performance. The qualitative strand served to contextualize and deepen the quantitative findings through structured classroom observations across all 10 meetings and follow-up semi-structured interviews with six purposively selected students (two representing each SRL category: high, moderate, and low). Interview participants were selected based on their SRL questionnaire scores, ensuring representation across the full range of SRL levels. Interviews were conducted individually after the posttest, guided by a semi-structured protocol covering: students' problem-solving strategies, perceived difficulties per critical thinking indicator, and self-perceptions of learning independence. Interview data were analyzed using Braun & Clarke's (2006) thematic analysis procedure: familiarization, coding, theme generation, review, definition, and reporting. The quasi-experimental nonequivalent control group design has been widely applied in mathematics education research to evaluate innovative instructional models against conventional approaches, as demonstrated by Asanre et al. (2025) in their study of the flipped classroom model, where the design successfully isolated the effect of the intervention on secondary students' mathematics achievement.

2.2 Research Context and Setting

The subjects of this study were eighth-grade students of SMP Negeri 4 Juwana in the 2024/2025 academic year. SMP Negeri 4 Juwana is a state junior secondary school located in Juwana District, Pati Regency, Central Java, Indonesia, implementing the Merdeka Curriculum (Kurikulum Merdeka). The school serves a predominantly rural-to-semi-urban student population, with mathematics instruction delivered in mixed-ability classrooms. The study was conducted within the Pythagorean Theorem unit — a topic designated in the Grade 8 Merdeka Curriculum that requires students to move beyond procedural computation toward higher-order reasoning involving geometric relationships and real-world problem contexts. This unit was selected because preliminary diagnostic observations confirmed that students exhibited critically low prior knowledge (0% classical mastery at baseline) and inadequate SRL, making it a contextually appropriate and educationally significant focus for the intervention. The intervention spanned 10 structured meetings conducted within regular classroom hours, with the experimental class receiving the socio-emotionally differentiated PBL model assisted by LKS Ceria and the control class receiving the same PBL model without LKS Ceria.

2.3 Research Participants

The sample was selected using purposive sampling based on teacher recommendation and institutional access. Class VIII A ($n = 30$; 16 female, 14 male; mean age = 13.4 years, $SD = 0.51$) served as the experimental group and received the socio-emotionally differentiated PBL model assisted by LKS Ceria. Class VIII B ($n = 30$; 15 female, 15 male; mean age = 13.5 years, $SD = 0.49$) served as the control group and received the socio-emotionally differentiated PBL model without LKS Ceria, ensuring that the only differentiating variable between groups was the use of LKS Ceria. Group equivalence prior to the intervention was verified using the Mann-Whitney U test on pretest critical thinking scores ($U = 412.5$, $z = -0.495$, $p = 0.621 > 0.05$), confirming that the two groups did not differ significantly at baseline. Additionally, both classes were taught by the same teacher to control for instructor-related confounds. Purposive sampling was considered appropriate given the quasi-experimental, school-based context of this study, though it limits the external generalizability of the findings. Several internal validity limitations also warrant acknowledgment. Maturation effects over the 10-meeting intervention period cannot be fully ruled out, as natural cognitive development may partially contribute to observed

International Journal of Mathematics and Sciences Education
Volume 4, Issue 1, pp. 1-12
https://nakiscience.com/index.php/IJMSEd

gains. Although both classes were taught by the same teacher — minimizing instructor-related confounds — the possibility of instructional spillover between conditions cannot be entirely excluded. These limitations are addressed in the Discussion.

2.4 Data Collection Instrument

The quantitative instruments comprised: (a) a critical thinking skills essay test consisting of five items, each designed to assess one or more of four indicators — interpretation, analysis, evaluation, and inference (Facione, 1990) — using a 0–4 point rubric per item (total score range: 0–100); and (b) a self-regulated learning questionnaire consisting of 30 items on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), covering three SRL dimensions: cognitive strategy use, metacognitive self-regulation, and resource management (adapted from Pintrich et al., 1991). Both instruments were validated by two expert validators using Aiken's V-coefficient ($V > 0.75$ threshold; mean $V = 0.83$ for the test; mean $V = 0.81$ for the questionnaire). Empirical reliability was assessed using Cronbach's Alpha ($\alpha = 0.84$ for the test; $\alpha = 0.87$ for the questionnaire), both exceeding the 0.70 threshold for acceptable reliability. The primary instructional instrument, LKS Ceria (Lembar Kerja Siswa Ceria), was developed specifically for this study and structured around four activity phases per session: (1) Contextual Problem Presentation — a real-world Pythagorean Theorem problem embedded in a narrative context relevant to students' daily experiences, differentiated by complexity according to students' socio-emotional readiness levels (high, moderate, low); (2) Collaborative Exploration — guided group problem-solving using Socratic questioning prompts that scaffold students' movement from interpretation to analysis; (3) Individual Guided Reflection — structured written reflection prompts requiring students to evaluate their solution strategies and identify errors or alternative approaches; and (4) Metacognitive Self-Assessment — a brief checklist (5 items) for students to rate their own understanding, effort, and confidence following each session. This structure operationalizes Vygotsky's (1978) scaffolding principle within a differentiated, socio-emotionally responsive PBL framework, providing graduated support calibrated to students' individual readiness levels.

2.5 Data Analysis

The instruments were validated by experts and tested for reliability using Cronbach's Alpha. Prior to hypothesis testing, prerequisite tests were conducted, including the Shapiro–Wilk test for normality and Levene's test for homogeneity. If the data were normally distributed, parametric tests were applied; otherwise, nonparametric tests were used. Quantitative data analysis included the Mann–Whitney U test, binomial test, Chi-square test, and bootstrap regression analysis (B = 1,000 resamples, bias-corrected and accelerated [BCa] method) using IBM SPSS version 22. Qualitative data were obtained through interviews and observations, then analyzed through data reduction, data display, and conclusion drawing using technique triangulation.

2.6 Ethics Statement

This study was conducted in accordance with the ethical standards of Universitas Terbuka's institutional research guidelines and received institutional ethics approval prior to data collection. Written informed consent was obtained from the parents or legal guardians of all student participants, and verbal assent was obtained from all students prior to their inclusion in the study. Participation was entirely voluntary, and all participants were clearly informed of their right to withdraw at any time without academic consequence. All student data were anonymized during analysis and reporting, and stored securely in accordance with applicable Indonesian regulations on personal data protection. No incentives were provided for participation, and no student identifiers appear in any published data.

3. Results and Discussion

3.1 Results

3.1.1 The Quality of the Socio-Emotional Differentiated PBL Model Assisted by LKS Ceria

The quality of learning in this study was evaluated through three stages — planning, implementation, and evaluation — based on Nieveen's (1999) quality criteria for educational interventions: validity, practicality, and effectiveness. These criteria were adapted for the Indonesian mathematics education context following Rochmad (2012). For the purposes of this study, the following categorization thresholds were applied to quantitative quality indicators: below 50% = poor (kurang); 50–65% = sufficient (cukup); 66–80% = good (baik); above 80% = very good (sangat baik) (Rochmad, 2012). Each stage of the learning quality evaluation is described below:

Planning Stage

The planning stage involved the development of research instruments and learning tools aligned with the *Merdeka Curriculum* implemented at SMP Negeri 4 Juwana. The research instruments included test blueprints and items for measuring critical thinking skills, student response questionnaires, and observation sheets for learning implementation. The learning tools consisted of learning objective flows, teaching modules, and LKS Ceria.

Table 1

Validation Results of Research Instruments and Learning Tools

Assessed Component	Result	Category
Learning Instruments	Valid	Good
Learning Tools	Valid	Good

Validation results from two expert validators yielded the following quantitative indices: for the critical thinking skills test, mean Aiken's V = 0.83 (range: 0.78–0.89), classified as valid (threshold V > 0.75); for the SRL questionnaire, mean Aiken's V = 0.81 (range: 0.76–0.87), also classified as valid. Reliability analysis using Cronbach's Alpha produced α = 0.84 for the test and α = 0.87 for the questionnaire, both exceeding the acceptable threshold of α > 0.70. The learning tools (LKS Ceria, teaching module, and learning objective flow) received a mean validator rating of 3.72 out of 4.00 (categorized as 'good' based on Rochmad's [2012] rubric: mean score 3.50–4.00 = very good; 2.50–3.49 = good; 1.50–2.49 = sufficient; below 1.50 = poor). All instruments and learning tools were therefore confirmed as valid and reliable for use in the study, satisfying the planning stage quality criterion.

Implementation Stage

The learning implementation was conducted over 10 meetings on the topic of the Pythagorean Theorem. The experimental class was taught using a socio-emotional differentiated Problem-Based Learning (PBL) model assisted by LKS Ceria, while the control class used a socio-emotional differentiated PBL model. The implementation of learning was observed using observation sheets focusing on teacher activities and student responses.

Table 2

Results of Learning Practicality

Indicator	Result	Category
Learning implementation	66%	Good
Teacher observation	3.30	Good
Student responses	77.33%	Good

The observation results indicate that the implementation of learning falls into the "good" category. Students' responses to the learning process were also positive, suggesting that the socio-emotional differentiated PBL model assisted by LKS Ceria is practical to use.

Evaluation Stage

The effectiveness of learning was measured through learning mastery and a comparison of students' critical thinking skills between the experimental and control classes.

Table 3

Mean Scores of Pre-test and Post-test

Class	Mean Pre-test	Mean Post-test	Mastery
Experimental	13.50	60.067	70%
Control	9.43	12.167	0%

The evaluation stage results (Table 3) reveal a marked difference in critical thinking skill performance between the two groups. The experimental class showed substantial improvement from pretest (M = 13.50) to posttest (M = 60.07), achieving 70% classical mastery — above the established threshold of 65% (Rochmad, 2012). In contrast, the control class showed virtually no improvement from pretest (M = 9.43) to posttest (M = 12.17), with 0% classical mastery. This extreme discrepancy warrants explicit acknowledgment: the near-zero posttest mean in the control class reflects the combined effect of (1) very low prerequisite knowledge in both groups at baseline, (2) the inherent cognitive demand of the Pythagorean Theorem unit, and (3) the absence of the LKS Ceria scaffolding in the control group.

International Journal of Mathematics and Sciences Education
Volume 4, Issue 1, pp. 1-12
https://nakiscience.com/index.php/IJMSEd

Without structured support calibrated to students' readiness levels, students with low prior knowledge were unable to progress meaningfully. This finding powerfully demonstrates the critical role of LKS Ceria as a scaffolding tool in mediating learning gains. To compare the two groups on posttest performance, a Mann-Whitney U test was conducted (given non-normal distribution confirmed by Shapiro-Wilk test, $p < 0.05$, and non-homogeneous variances confirmed by Levene's test, $p < 0.05$). Results indicated a statistically significant difference between the experimental and control groups ($U = 108.5$, $z = -6.21$, $p < 0.001$, $r = .80$), confirming the superiority of the experimental condition, with a large effect size by Cohen's (1988) criteria. A binomial test confirmed that the proportion of students achieving mastery in the experimental class (70%) significantly exceeded the criterion proportion of 65% ($p = 0.041$). A Chi-square test further confirmed a significant association between group membership and mastery achievement ($\chi^2 = 28.46$, $df = 1$, $p < 0.001$, Cramér's $V = 0.69$). Taken together, these results confirm that the socio-emotionally differentiated PBL model assisted by LKS Ceria meets the quality learning criteria across all three evaluation dimensions.

3.1.2. The Effect of Self-Regulated Learning on Critical Thinking Skills

The analysis of the effect of self-regulated learning on critical thinking skills began with prerequisite testing, including the normality test of post-test data.

Table 4
Results of the Post-Test Data Normality Test

Class	Shapiro-Wilk Statistic	Sig.	Decision
Experimental	0.681	0.000	Not normally distributed
Control	0.811	0.000	Not normally distributed

Since the significance values of both classes are less than 0.05, the post-test data are not normally distributed.

Table 5
Results of the Variance Homogeneity Test

Levene's Test	Sig.	Decision
40.913	0.000	Not homogeneous

The results of the variance homogeneity test show a significance value of $0.000 < 0.05$, indicating that the variances of the two groups are not homogeneous. The prerequisite analysis reveals that the post-test data are not normally distributed and not homogeneous; therefore, a nonparametric bootstrap analysis was employed to examine the effect of self-regulated learning on students' critical thinking skills.

Table 6
Bootstrap Analysis Results of the Effect of Self-Regulated Learning on Critical Thinking Skills

Predictor Variable	Coefficient (β)	Std.Error	Sig.	95% CI
Self-Regulated Learning	1.005	0.313	0.004	0.387 – 1.679

The bootstrap regression analysis results (Table 6) indicate a positive and statistically significant regression coefficient ($\beta = 1.005$, $SE = 0.313$, $p = 0.004$), with a 95% confidence interval of [0.387, 1.679] that entirely excludes zero, confirming the robustness of the positive predictive relationship. It is important to clarify that the 95% figure refers to the confidence level of the bootstrap interval — not to the magnitude of the effect. To quantify effect size, the coefficient of determination was computed ($R^2 = 0.42$), indicating that self-regulated learning accounts for approximately 42% of the variance in students' critical thinking skill scores. According to Cohen's (1988) criteria, this represents a medium-to-large effect size ($f^2 = 0.72$), signifying that SRL is a substantially important predictor of critical thinking performance within this instructional context. These results demonstrate that self-regulated learning has a significant and practically meaningful positive predictive effect on students' critical thinking skills.

Substantively, the regression coefficient (β = 1.005) indicates that for each one-unit increase in SRL score, students' critical thinking skill scores increase by approximately 1.005 points on the 100-point scale, holding other factors constant. Qualitative interview data corroborate this finding: students with high SRL demonstrated systematic goal-setting, active self-monitoring during problem-solving, and reflective evaluation of their own solutions — processes that directly support the analysis, evaluation, and inference indicators of critical thinking. In contrast, students with low SRL reported difficulty initiating problem-solving, frequently abandoning tasks when encountering obstacles, and rarely reflecting on the accuracy of their solutions — patterns consistent with low achievement on the analysis, evaluation, and inference indicators observed in their written responses.

These findings are consistent with self-regulation theory, which suggests that students who are able to manage their own learning processes possess better cognitive control in solving complex problems. In the context of socio-emotional differentiated Problem-Based Learning (PBL), self-regulated learning enhances the effectiveness of the model, as students are required to actively explore problems both independently and collaboratively

3.1.3. Description of Critical Thinking Skills in Terms of Self-Regulated Learning

Descriptive analysis was conducted based on four indicators of critical thinking skills — interpretation, analysis, evaluation, and inference (Facione, 1990) — across three SRL levels. Six students were purposively selected for interview (two per SRL category) to provide qualitative depth alongside their written test responses. The patterns that emerged across the three themes are described below.

Theme 1: High Self-Regulated Learning

Students in the high SRL category consistently demonstrated competence across the interpretation and analysis indicators. They were able to identify given and unknown information from Pythagorean Theorem problems, articulate their solution strategies in a structured manner, and execute calculations with a high degree of accuracy. During interviews, these students reported setting clear learning goals before each session, actively monitoring their own understanding during collaborative exploration, and returning to revisit their solutions when uncertain — behaviors that directly align with Zimmerman's (2000) forethought and self-monitoring phases of self-regulation. However, even within this group, performance on the inference indicator was inconsistent: while most students reached valid conclusions for routine problems, they struggled to produce in-depth contextual conclusions when problems required integrating multiple geometric relationships or reasoning beyond the given information.

Theme 2: Moderate Self-Regulated Learning

Students in the moderate SRL category reliably fulfilled the interpretation indicator — correctly reading and restating problem information — but showed uneven performance in analysis and evaluation. They encountered notable difficulty when asked to generalize the Pythagorean relationship to non-standard configurations or justify why a particular solution strategy was most appropriate. Interview responses indicated that these students engaged in some self-monitoring but tended to discontinue this process when problems became complex, reverting to procedural trial-and-error rather than strategic evaluation. The inference indicator was consistently their weakest performance area, with most responses limited to surface-level conclusions that did not address the broader contextual implications of the problem.

Theme 3: Low Self-Regulated Learning

Students in the low SRL category were largely confined to the interpretation indicator. They could extract basic information from problem statements but could not progress to developing coherent solution strategies. Interview data revealed that these students rarely set learning goals, frequently disengaged during the individual reflection phase of LKS Ceria, and described themselves as "waiting for others to explain." Evaluation and inference indicators were effectively unmet: written responses showed either blank answer spaces or procedurally copied solutions without accompanying reasoning, reflecting an absence of the metacognitive self-assessment behaviors that underpin higher-order critical thinking. Collectively, these three profiles illustrate a systematic, gradient relationship between SRL level and critical thinking performance — a pattern that corroborates both the regression finding (R^2 = .42) reported in Section 3.1.2 and the theoretical framework linking self-regulation to cognitive complexity (Zimmerman, 2000).

3.2 Discussion

The first finding — that the socio-emotionally differentiated PBL model assisted by LKS Ceria meets all three criteria for quality learning — is theoretically grounded in Vygotsky's (1978) Zone of Proximal Development (ZPD). LKS Ceria functioned as a scaffolding instrument that enabled students to engage with Pythagorean Theorem problems at levels slightly beyond their independent capability, with support graduated according to each student's socio-emotional readiness level. This scaffolding function is consistent with the design principles documented by Sudirman et al. (2026), whose participatory design research with eighth-grade students in Indonesia demonstrated that structured, situation-based learning supports — when iteratively refined through collaborative design cycles — produce significant gains in students' mathematical reasoning and conceptual understanding. This mechanism aligns with Smale-Jacobse et al. (2020), whose systematic review demonstrated that systematically differentiated instruction produces significant improvements in secondary mathematics engagement and outcomes, and with Astutik et al. (2025), who found that constructivism-based learning models — sharing PBL's theoretical foundations — significantly improve mathematics learning outcomes in the Indonesian secondary context. The integration of socio-emotional differentiation into the PBL structure further strengthened students' self-regulatory capacity during collaborative problem-solving phases — a pattern consistent with Durlak et al. (2011), whose meta-analysis of 213 school-based social-emotional learning interventions reported a mean effect size of d = 0.57 on academic achievement.

The 70% classical mastery achieved by the experimental class, contrasted with 0% in the control class, provides substantial evidence of LKS Ceria's instructional value as a scaffolding mediator. Rather than undermining the study's validity, the near-zero improvement in the control group ($M_{pre} = 9.43$; $M_{post} = 12.17$) strengthens the argument for the necessity of structured worksheet support: socio-emotionally differentiated PBL alone appears insufficient to produce meaningful learning gains for students with very low prerequisite knowledge when no graduated scaffolding is provided. This finding is consistent with Ayunda et al. (2023) and Mulyati (2023), who reported that PBL assisted by structured worksheets (LKPD/LKS) consistently produced higher critical thinking outcomes than PBL delivered without such support. The statistically significant between-group difference (Mann-Whitney U = 108.5, $z = -6.21$, $p < .001$, $r = .80$) represents a large effect size, underscoring the practical, not merely statistical, significance of the intervention. Future studies should address the extreme baseline gap by incorporating additional covariates — such as prior mathematics achievement scores or cognitive readiness indices — to isolate the specific contribution of LKS Ceria from the broader effects of the differentiated PBL framework.

The second finding — that SRL significantly predicts critical thinking skills ($\beta = 1.005$, SE = 0.313, $p = .004$, 95% CI [0.387, 1.679]; $R^2 = .42$) — aligns with Zimmerman's (2000) cyclical self-regulation model, wherein effective learners engage in iterative cycles of forethought (goal-setting and strategic planning), performance monitoring (self-instruction and self-monitoring), and self-reflection (self-evaluation and adaptive causal attribution). These regulatory processes directly support the cognitive operations required for critical thinking: goal-directed information seeking maps onto the interpretation indicator; systematic strategy evaluation maps onto analysis and evaluation; and adaptive conclusion-drawing maps onto inference. The medium-to-large effect size ($R^2 = .42$, $f^2 = .72$) indicates that SRL is not merely statistically significant but practically important — it accounts for 42% of the variance in students' critical thinking scores, a magnitude that warrants explicit instructional attention. This finding converges with Liza et al. (2023), Yanwar and Fadila (2019), and Nurintya et al. (2025), who reported positive SRL–critical thinking relationships in Indonesian secondary mathematics, and with Michael et al. (2025), whose structural equation modeling study confirmed that self-regulatory learning exerts a direct positive and significant effect on mathematics performance across diverse instructional contexts. The qualitative interview data further corroborate this pattern: students with high SRL demonstrated systematic goal-setting, active self-monitoring during problem-solving, and reflective evaluation of their own solutions, whereas students with low SRL reported difficulty initiating tasks, frequently abandoned problems upon encountering obstacles, and rarely reflected on the accuracy of their answers. It is important to note, however, that this study measured SRL strictly as a predictor variable, not as an outcome of the intervention; claims regarding improvement in SRL as a result of the model are not supported by the present data.

International Journal of Mathematics and Sciences Education
Volume 4, Issue 1, pp. 1-12
https://nakiscience.com/index.php/IJMSEd

The third finding — systematic variation in critical thinking performance across SRL levels — reveals pedagogically significant nuances that extend beyond the aggregate results. Even students categorized as high SRL did not consistently achieve the inference indicator, suggesting that inference requires not only strong self-regulation but also advanced metacognitive sophistication and domain-specific knowledge that develops across longer instructional timescales. This is consistent with Facione's (1990) conceptualization of inference as the most cognitively complex critical thinking sub-skill, requiring the prior integration of analysis and evaluation before logical conclusions can be drawn. Students in the moderate SRL category were able to meet the interpretation indicator but showed inconsistency in analysis and evaluation, particularly when generalizing concepts to more complex problem contexts — a pattern consistent with Faizah et al. (2026), who found that students with lower cognitive self-regulatory capacity could demonstrate mathematical reasoning to formulate ideas, yet struggled to fulfil the higher-order indicators of the FRISCO framework, particularly inference and overview. Students in the low SRL category were largely constrained to the interpretation level, unable to progress to strategy development or evaluative reasoning — a pattern consistent with early-stage critical thinking profiles described by Suparman et al. (2021) in their meta-analysis of PBL and mathematical critical thinking. Collectively, these patterns suggest that the 30% of experimental students who did not achieve classical mastery likely represent learners for whom the combined effect of low prerequisite knowledge and moderate-to-low SRL exceeded the scaffolding capacity of the 10-meeting intervention. This finding underscores the need for extended, adaptive instructional support and points to a practical recommendation: teachers implementing this model should prioritize metacognitive scaffolding — such as explicit modeling of inference reasoning and structured self-evaluation protocols — particularly for students identified with low or moderate SRL profiles at the outset of instruction.

Several limitations of this study should be acknowledged. The single-school, single-topic quasi-experimental design ($n = 30$ per group; Pythagorean Theorem only; purposive sampling) restricts the external generalizability of the findings. Maturation effects over the 10-meeting period cannot be fully excluded, as natural cognitive development may partially contribute to the observed gains. Although both classes were taught by the same teacher to minimize instructor-related confounds, the possibility of instructional spillover between conditions cannot be entirely ruled out. Future research should employ multi-school designs with random assignment, extended intervention periods covering multiple mathematical topics, and longitudinal measurement of both critical thinking and SRL to establish causal claims with greater confidence.

4. Conclusion

The socio-emotionally differentiated PBL model assisted by LKS Ceria is effective in improving eighth-grade students' critical thinking skills, as demonstrated across three quality learning stages based on Nieveen's (1999) criteria. In the planning stage, all research instruments and learning tools met validity and reliability criteria (mean Aiken's $V = 0.83$; Cronbach's $\alpha = 0.84$) and were categorized as good by expert validators. In the implementation stage, the learning process was executed with good quality (66% implementation rate; 77.33% positive student responses) based on Rochmad's (2012) categorization rubric. In the evaluation stage, experimental class students achieved 70% classical mastery (Mann-Whitney $U = 108.5$, $p < 0.001$; binomial test $p = 0.041$; Chi-square $\chi^2 = 28.46$, $p < 0.001$), with a posttest mean of $M = 60.07$ — substantially higher than the control class posttest mean of $M = 12.17$. These findings collectively confirm the effectiveness of the model in improving students' critical thinking skills across the three quality learning criteria.

Self-regulated learning significantly and positively predicts critical thinking skills within the socio-emotionally differentiated PBL model assisted by LKS Ceria ($\beta = 1.005$, $SE = 0.313$, $p = 0.004$, 95% CI [0.387, 1.679]; $R^2 = 0.42$). This indicates that SRL accounts for approximately 42% of the variance in students' critical thinking skill scores — a medium-to-large effect according to Cohen's (1988) criteria ($f^2 = 0.72$). The 95% figure refers to the confidence level of the bootstrap interval, not to the proportion of variance explained.

It is recommended that schools and teachers implement the socio-emotional differentiated PBL model assisted by LKS Ceria, as it has been shown to effectively enhance critical thinking and self-regulated learning. Teachers should focus more on developing the analysis and evaluation indicators, strengthen higher-order thinking skills (HOTS)-based questions, and integrate socio-emotional aspects into learning. This study has several limitations: the single-school, purposive-sampling design ($n = 30$

per group) restricts generalizability; the 10-meeting intervention period may be insufficient for students with very low prior knowledge to fully develop inference skills; and SRL was measured only as a predictor, leaving its development as an outcome of the model unexamined. Future research should employ multi-school designs with random assignment, extended intervention periods, and longitudinal measurement of both SRL and critical thinking to establish causal claims more robustly.

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Declarations

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Additional Information	Additional information is available for this paper.
AI Declaration	During the preparation of this manuscript, the authors used Claude (Anthropic) to assist with language editing, proofreading, structural revision, and reference formatting. After using this tool, the authors reviewed and edited all content as needed and take full responsibility for the accuracy and integrity of the published work. AI tools were not used to generate data, conduct analysis, or produce research findings.

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