

PATTERNS AND GAPS INTEGRATION OF PBL, STEAM, AND METACOGNITIVE PROMPTS TOWARDS STUDENTS' CRITICAL THINKING

Novemia Yohana Shinta Maharani¹, Parno¹, Purbo Suwasono¹, dan Hartatiek¹

¹ Departement of Physics Education, State University of Malang, Indonesia

Corresponding author email: parno.fmipa@um.ac.id

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Abstract :

This systematic literature review maps and synthesizes empirical evidence on Problem Based Learning (PBL), STEAM/STEM, and metacognitive prompts in relation to students' critical thinking skills. Guided by the PRISMA 2020 framework, studies were retrieved from Scopus and screened through identification, screening, eligibility, and inclusion stages, resulting in 31 empirical articles published between 2021 and 2025. The findings show an increasing publication trend peaking in 2024, with secondary-school contexts and quasi-experimental designs predominating. PBL was the most frequently represented component (64.5%), followed by STEAM/STEM (41.9%) and metacognitive strategies (12.9%). Most studies reported positive contributions to critical thinking through distinct mechanisms: PBL through problem-solving, STEAM/STEM through interdisciplinary learning, and metacognitive strategies through regulation of thinking processes. However, none of the 31 studies simultaneously integrated PBL, STEAM/STEM, and metacognitive prompts with critical thinking within a coherent learning design. This finding reveals a clear empirical gap and supports the development and validation of an integrated PBL–STEAM model supported by metacognitive prompts, particularly for secondary science and physics education.

Keywords: Critical Thinking; Metacognitive Prompts; PBL-STEAM Integration

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INTRODUCTION

The educational paradigm in the 21st century has shifted from merely mastering material to developing thinking skills. In a situation characterized by an abundance of information and the complexity of real-world problems, students are no longer satisfied with merely mastering concepts. They are also required to be able to analyze, evaluate, and construct logical arguments (Winaryati et al., 2025). Critical thinking, understood as a reflective cognitive process for determining what is worthy of belief or action, is now recognized as a core competency in the global education system (Amanda et al., 2023). Critical thinking skills are becoming increasingly crucial in science education because science requires evidence-based reasoning, hypothesis testing, and comprehensive evaluation of claims (Sujanem & Putu Suwindra, 2023).

However, student achievement in critical thinking remains a serious issue in various countries, including Indonesia. PISA 2022 data shows that although Indonesia's ranking increased by 5–6 positions compared to 2018, scores in each ability aspect actually decreased, indicating that students' higher-order reasoning abilities have not developed optimally (Ariyanti et al., 2024). This low critical thinking ability is inextricably linked to learning practices that are still dominated by a transmissive approach, where teachers act as the primary source of information and students become passive recipients (Ubaidillah, 2025). This situation encourages the need for a transformation in learning models that foster higher-order thinking processes in every learning activity.

Problem Based Learning (PBL) is one of the most theoretically and empirically studied learning models for developing critical thinking. This model places authentic problems as the starting point of learning, encouraging students to actively construct knowledge through investigation, discussion, and reflection (Suyitno et al., 2024). Various studies have demonstrated the effectiveness of PBL in improving critical thinking in various learning contexts. Sari et al. (2025), for example, combined PBL with a flipped classroom and found that this learning model effectively improved critical thinking in students with low, medium, and high academic abilities. Furthermore, Pitorini et al. (2024) demonstrated that PBL enriched with Socratic dialogue through e-modules significantly improved the critical thinking of junior high school students. Furthermore, Amanda et al. (2023) demonstrated that PBL integrated with complexity science principles was more effective than conventional PBL or direct learning.

Despite strong evidence regarding the effectiveness of PBL, some researchers have noted that implementing PBL in isolation without an interdisciplinary contextual framework or support mechanisms to help students organize their thought processes has not yielded optimal results. Pertiwi et al. (2024) argue that 21st-century science education requires an approach that is not only pedagogically active but also contextually rich, enabling students to view problems from diverse disciplinary perspectives. This need has prompted researchers to explore integrating PBL with other instructional approaches. In recent years, the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach has gained increasing attention as an interdisciplinary framework that enriches science learning. Unlike monodisciplinary instruction, STEAM encourages students to solve problems by integrating various scientific perspectives, including artistic and creative dimensions often overlooked in conventional science education (Sari et al., 2025). A study by Wilson et al. (2021) involving 318 K-12 students across seven U.S. states demonstrated that transdisciplinary STEAM learning can simultaneously enhance critical and creative thinking, with particularly strong effects observed at the secondary school level. Similar findings were reported by Putri et al. (2023), who demonstrated the effectiveness of STEAM-based blended learning on the critical thinking skills of 180 junior high school students in Yogyakarta, and by Sari et al. (2025), who developed a STEAM integration framework to enhance critical thinking skills in science education.

Beyond the dimensions of learning models and approaches, there is an internal aspect that contributes to the successful development of critical thinking: metacognitive ability. Metacognition refers to an individual's awareness of their own thought processes and the ability to consciously regulate those processes including planning thinking strategies, monitoring comprehension, and evaluating the quality of reasoning (Marthaliakirana et al., 2022). In a study involving 678 seventh-grade students in Turkey, Dökmecioğlu et al. (2022) found that metacognitive self-regulation strategies act as a significant mediator between constructivist learning environments and critical thinking dispositions. These findings are supported by Pereles et al. (2024), who demonstrated that the use of metacognitive strategies via digital tools significantly enhances students' critical thinking abilities in online learning. These results indicate that metacognition is not merely a supporting skill but a crucial component that facilitates the critical thinking process itself.

Despite these findings, empirical research indicates that these three components have evolved along relatively separate paths. Some studies have combined PBL with STEM/STEAM but have not incorporated metacognitive support mechanisms. In this context, Rizki & Suprpto (2024) developed Project-Oriented PBL using SR-STEM projects, successfully enhancing high school students' critical thinking skills regarding renewable energy, while Pertiwi et al. (2024) designed a STEM-based Problem-Based Learning approach enhanced with e-modules and PhET virtual simulations for thermodynamics. Conversely, research integrating PBL with metacognitive prompts was conducted by Marthaliakirana et al. (2022) using a PBL model with metacognitive prompts (M-PBL) involving 121

high school students; this model proved significantly more effective at improving argumentation and critical thinking than conventional PBL. Meanwhile, STEAM studies such as those by Wilson et al. (2021), Putri et al. (2023), and Küçük et al. (2023) demonstrate the potential of this interdisciplinary approach for developing critical thinking, yet they have not simultaneously integrated it with PBL and metacognitive support mechanisms.

Taken together, the research gap lies not only in the absence of studies combining these three components but also in the lack of a systematic mapping regarding the extent to which they have been integrated in existing research. Previous studies have tended to focus on relationships or combinations involving two components such as PBL with STEM/STEAM or PBL with metacognitive strategies whereas STEAM research generally emphasizes interdisciplinary contexts without structured learning models or explicit metacognitive support. This situation reveals fragmentation in the research landscape: PBL serves as a pedagogical framework for problem-solving, STEAM as an interdisciplinary context, and metacognitive guidance as a mechanism for regulating thought processes, yet the three have not been mapped as a unified conceptual whole. Therefore, a review is needed that not only summarizes the effectiveness of each approach but also identifies integration patterns, methodological characteristics, and the gaps inherent in their combination.

Theoretically, these three components offer synergistic potential when integrated. PBL provides a pedagogical structure that encourages students to actively engage in problem-solving; STEAM enriches the problem context with an interdisciplinary perspective requiring reasoning from multiple viewpoints; and metacognitive prompts assist students in consciously planning, monitoring, and evaluating their thought processes during problem-solving (Marthaliakirana et al., 2022; Dökmecioğlu et al., 2022). However, the relationship between them has previously been understood largely in conceptual terms or through only partial combinations of the components. Therefore, a systematic literature review is needed to provide an empirical overview of whether and how these three components have been integrated in existing research.

To address this gap, this study conducts a Systematic Literature Review (SLR) based on PRISMA 2020 guidelines, guided by four research questions: (RQ1) what are the distribution and trends of research on PBL, STEAM, and metacognitive strategies within the context of critical thinking for the 2021–2026 period; (RQ2) what are the methodological characteristics of existing research; (RQ3) to what extent has the integration of these components been achieved, and what are the implications of their fragmentation; and (RQ4) what are the key research gaps that provide empirical justification for developing a STEAM-integrated PBL model supported by metacognitive prompts? Thus, this review goes beyond merely identifying the effectiveness of each individual approach; it offers new insights by mapping the integration levels of the three components, identifying research fragmentation patterns, and pinpointing gaps in the integration of PBL, STEAM, and metacognitive prompts.

The urgency of this research lies in a specific structural gap: while PBL, STEAM, and metacognitive prompts have individually proven effective in fostering critical thinking, they have not yet been tested simultaneously within a coherent instructional design; consequently, their potential synergy lacks an empirical basis. The primary novelty of this review lies in its explicit focus on mapping the integration of these three components within a single analytical framework using the PRISMA 2020 protocol, rather than merely reviewing the effectiveness of PBL, STEAM, or metacognition in isolation or in pairwise combinations. The analysis reveals a complete absence of studies falling into the "full integration" category (PBL + STEAM + metacognitive prompts) specifically, zero out of the 31 articles published between 2021 and 2025. These findings provide empirical evidence of research fragmentation a phenomenon not previously demonstrated through the simultaneous mapping of these three components in a single review. Thus, the review's main contribution goes beyond merely suggesting the potential for integrating these three components; it demonstrates, based on the literature mapping, that such full integration is currently unrepresented in the analyzed studies. This insight provides empirical justification for developing an integrated PBL-STEAM learning model supported by metacognitive prompts, particularly for the topic of Momentum and Impulse at the high school level the context for the author's subsequent research.

RESEARCH METHOD

Research Design

This study employed a qualitative design using the Systematic Literature Review (SLR) method. SLR is a secondary research method that aims to identify, evaluate, and synthesize all empirical evidence relevant to the research question in a systematic, transparent, and replicable manner. The review was conducted based on the PRISMA 2020 guidelines developed by Page et al. (2021), which serve as a methodological framework to ensure completeness and transparency at every stage of the review process.

Eligibility Criteria

To ensure the relevance and quality of the articles reviewed, inclusion and exclusion criteria were established a priori before the literature search. These criteria served as the basis for selecting articles that align with the research focus and objectives. A complete breakdown of the criteria operationalized in this review is presented in Table 1.

Table 1. Inclusion Criteria for Article Selection

Code	Inclusion Criteria	Description
IC1	Empirical research articles	Not an opinion, editorial, or conceptual article; must have primary data
IC2	Using PBL or its variations	Problem Based Learning as the main learning model/approach or one of the variables
IC3	Contains STEAM/STEM and/or metacognitive prompts	Minimum one variable: STEAM/STEM integration or metacognitive prompts/strategies
IC4	Measuring critical thinking skills	Critical thinking as a dependent variable that is measured quantitatively or analyzed qualitatively
IC5	Published 2021–2026	Last 5 years span to ensure the freshness of the literature
IC6	Student or college student subjects	Subjects in the context of formal learning at school or college
IC7	Published in indexed journals	Scopus with full abstract
IC8	Minimum 2 main variables	Must contain at least PBL, STEAM, or metacognitive prompts

Table 1 summarizes the inclusion criteria applied to identify studies relevant to the objectives of this review. The criteria covered the research design, learning approaches, critical thinking outcomes, publication period, participants, indexing status, and the minimum number of relevant variables. These criteria were applied consistently during the screening process to ensure that the included studies were directly aligned with the research questions.

Table 2. Exclusion Criteria for Article Selection

Code	Exclusion Criteria Eksklusi	Description
EC1	Review article / SLR / meta-analysis	Systematic review, scoping review, meta-analysis, umbrella review, or erratum/correction
EC2	Does not discuss critical thinking	Does not measure or analyze critical thinking as a variable
EC3	Not using PBL/STEAM/metacognitive	There are no PBL, STEAM/STEM, or metacognitive prompts as variables.
EC4	Not relevant to educational context	Di luar konteks pendidikan formal (sekolah atau perguruan tinggi)
EC5	No complete abstract available	Only editorials, short opinions, erratums, or articles without abstracts
EC6	Subjects are not students/students of learning	Subjects: nurse practitioners, doctors, non-regular adult learners, workshop teachers

Code	Exclusion Criteria Eksklusi	Description
EC7	Pure correlation without intervention	Survey, SEM, correlation without learning intervention; not testing the model
EC8	R&D without CT effectiveness testing	Product development without testing the effectiveness of critical thinking

Table 2 presents the exclusion criteria used to remove studies that did not meet the scope of the review. Studies were excluded when they were non-empirical or review-based, lacked a focus on critical thinking, did not involve PBL, STEAM/STEM, or metacognitive components, fell outside the formal educational context, lacked a complete abstract, or did not involve relevant student participants. Studies without an intervention or effectiveness assessment of critical thinking were also excluded.

Database and Search Strategy

The literature search for this study was conducted through the Scopus database, selected for its extensive coverage of reputable, peer-reviewed scientific journals in the fields of science and education. The search strategy was designed using Boolean operators (AND, OR) to ensure all relevant articles were comprehensively identified. Three primary keyword combinations were used: (1) "Problem-Based Learning" AND "Critical Thinking"; (2) "STEAM" AND "Critical Thinking"; and (3) ("Metacognition" OR "Metacognitive Strategy") AND "Critical Thinking." The initial search yielded 188 articles before being filtered based on publication year and journal indexing. All retrieved articles were then exported and managed using a structured spreadsheet-based selection system. A deduplication process was performed to identify and remove duplicate articles before the screening stage. The literature search was conducted on March 29, 2026 (9:50 PM WIB), covering publications from January 2021 to March 2026.

Article Selection Process

The article selection process in this study followed the PRISMA 2020 process, which consists of four stages: Identification, Screening, Eligibility, and Inclusion. A PRISMA flowchart showing the number of articles at each stage is presented in Figure 1.

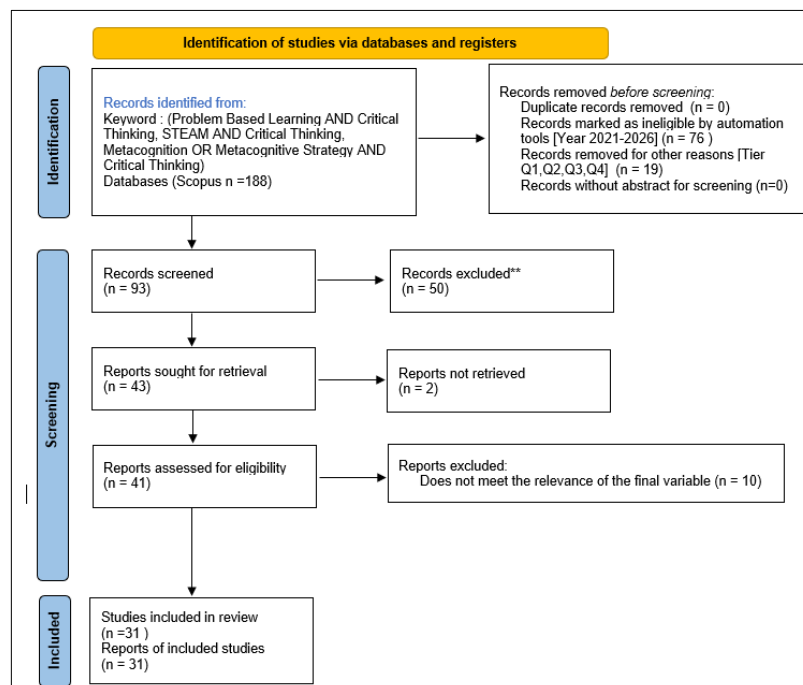


Figure 1. PRISMA 2020 Flowchart

In the Identification stage, 188 articles were obtained. After applying publication year restrictions (2021–2026) and Scopus indexing criteria, the number of articles was reduced to 93. During the screening stage, selection was based on titles and abstracts, resulting in the elimination of 50 articles. The primary reasons for exclusion included articles in the form of reviews or meta-analyses (n = 17),

the use of non-student subjects or contexts outside the scope of the study ($n = 16$), purely correlational research designs lacking an instructional intervention ($n = 8$), the absence of key research variables ($n = 7$), the lack of an abstract or classification as an editorial ($n = 1$), and research and development (R&D) studies lacking an effectiveness test ($n = 1$). Consequently, 43 articles proceeded to the eligibility assessment stage involving a full-text review. In the Eligibility stage, a full-text assessment was conducted, resulting in the elimination of two articles because they used a descriptive design and did not systematically measure critical thinking skills as an outcome variable, resulting in 41 eligible articles. Furthermore, in the Inclusion stage, 10 articles were excluded due to a lack of substantial relevance to the three main research constructs. Thus, the final number of articles analyzed in the synthesis was 31 articles.

Data Extraction

Data extraction was conducted using a standardized matrix to systematically record key information from each included article. Extracted variables included article identity (author and year of publication), journal name and Scopus quartile, learning model or approach used (PBL, STEAM, metacognitive prompts, or a combination), measured dependent variables, research design and methods, sample characteristics (educational level, sample size, and country), key findings related to critical thinking skills, and integration categories between components.

Data Analysis

Data analysis was conducted qualitatively through four iterative stages, referring to a thematic synthesis approach. The first stage was data reduction, which summarized the extracted information into a structured matrix. The second stage was categorization, where articles were grouped based on learning approach, measured variables, methodological design, and educational level. The third stage was narrative synthesis using a cross-case analysis approach to identify patterns, consistencies, differences, and gaps in integration between components. The final stage was drawing conclusions based on the convergence of empirical evidence from the various studies analyzed.

Quality Assessment and Risk of Bias

Quality assessment was conducted using evaluative criteria adapted from the educational research assessment framework, including: (a) clarity of the research design; (b) operational definitions and validity of critical thinking measures; (c) appropriateness of statistical analyses to the research design; (d) transparency of reporting (samples, instruments, and procedures); and (e) consistency in reporting the direction of the research results. All 31 included articles met these minimum quality thresholds. Consistency of inclusion decisions was also verified through a double-screening process of a random sample of 20% of articles by the principal investigator, with any discrepancies resolved through discussion. Risks of bias arising from the predominance of quasi-experimental designs, such as limitations of randomization and baseline differences between groups, are acknowledged and further discussed in the Discussion section.

RESULTS AND DISCUSSION

Overall Selection Results

Of the 188 articles obtained in the initial stage through the Scopus database, a step-by-step selection process using the PRISMA process yielded 31 articles that met the criteria and were used as the final analysis corpus. Table 3 presents a summary of the number of articles at each PRISMA stage along with the main reasons for exclusion during the selection process.

Table 3. Summary of PRISMA Stages

PRISMA Stages	Number of Articles	Additional Information
Identification	188 → 93	188 articles were identified. A total of 76 articles were excluded based on publication year constraints, and 19 articles based on Scopus indexing criteria, leaving 93 articles.

PRISMA Stages	Number of Articles	Additional Information
Screening	93 → 43	A total of 50 articles were excluded based on a review of titles and abstracts. The primary reasons were: reviews/meta-analyses (n = 17), non-student subjects/out-of-context (n = 16), correlational designs without intervention (n = 8), failure to include key variables (n = 7), lack of an abstract/editorial (n = 1), and R&D without an effectiveness test (n = 1).
Eligibility	43 → 41	Full-text screening resulted in the exclusion of two articles because they employed a descriptive design and did not systematically measure critical thinking skills as an outcome variable.
Inclusion (Final)	41 → 31	Ten articles were excluded due to a lack of sufficient substantive relevance to the focus on integrating three key constructs: PBL, STEAM, and metacognitive strategies. Thirty-one articles were included in the final synthesis.

During the screening phase, the largest number of exclusions resulted from review articles or meta-analyses (n = 17) and studies involving non-student subjects (n = 16), followed by correlational designs lacking interventions (n = 8), studies omitting key variables (n = 7), and in each case one article lacking an abstract (or an editorial) and one R&D study without an effectiveness test. These findings highlight the necessity of screening based on research context, design, and constructs, ultimately yielding 31 relevant articles for the final synthesis.

Publication Trends and Geographic Distribution

Publication trends based on keywords used in the search stage show a year-over-year increase. This increase reflects the growing attention paid to the research topic under study. This trend pattern can be seen more clearly in Figure 2 below.

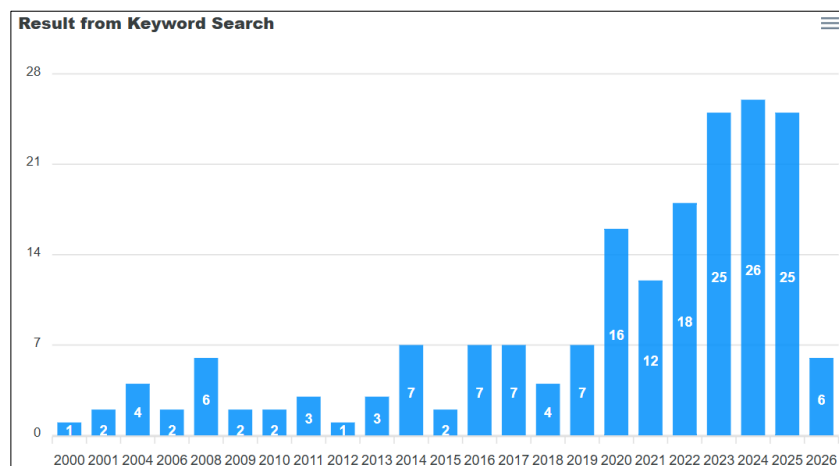


Figure 2. Annual Distribution of Articles by Keywords

The 31 articles included in this study cover the publication period from 2021 to 2026, although articles published in 2026 did not yet provide relevant contributions to the focus of the review. The annual distribution of the articles is presented in Table 4.

Tabel 4. Annual Distribution of Included Articles (2021–2026)

Year	n	Percentage (%)
2021	3	9,7
2022	4	12,9
2023	8	25,8
2024	10	32,3

Year	n	Percentage (%)
2025	6	19,4
2026	0	0,0

The number of publications increased from three articles in 2021 to ten articles in 2024, representing more than a threefold increase over four years, with 2023 being a particularly notable point of increase. Geographically, Indonesia dominated the number of publications, contributing approximately 13 of the 31 articles ($\pm 41.9\%$), followed by other countries such as Turkey, the United States, Saudi Arabia, Spain, and several countries in the Asian region. This dominance of research from Indonesia aligns with the direction of the national education policy, the Independent Curriculum, which emphasizes project-based learning and the development of higher-order thinking skills.

Educational Level and Disciplinary Context

Secondary school students were the most dominant research subjects, appearing in approximately 45% of the total articles analyzed. This was followed by elementary school students ($\pm 19\%$) and university students or those in higher education ($\pm 23\%$), while junior high school students comprised approximately 13%. The dominance at the secondary school level demonstrates the appropriateness of the implementation of PBL and STEAM approaches to the level of cognitive complexity of the science curriculum at this level. Topics such as thermodynamics, renewable energy, chemistry, and physics generally present authentic problems suitable for study through project-based and interdisciplinary approaches.

Methodological Characteristics

Quasi-experimental studies were the most frequent design, appearing in 16 of 31 articles (51,6%), as shown in Table 5. This pattern reflects the practical difficulty of applying full random assignment in formal educational settings. Other designs included experimental, mixed-methods, qualitative, R&D with efficacy testing, and descriptive or cross-sectional quantitative studies. The complete distribution of research design types used across all articles is presented in Table 5.

Table 5. Distribution of Research Designs

Research Design	n	Percentage (%)
Quasi-experimental (pretest–posttest)	16	51,6
Experimental/Other qualitative	9	29,0
Research & Development (R&D)	3	9,7
Qualitative	2	6,5
Mixed methods	1	3,2

The critical thinking measurement instruments used in all articles showed considerable variation. These included essay tests scored based on Facione's (2011) rubric, which covers interpretation, analysis, evaluation, inference, and explanation; the Watson–Glaser Critical Thinking Appraisal; the California Critical Thinking Dispositions Inventory (CCTDI); and a performance assessment instrument developed by the researchers. This variation in instruments limits direct quantitative comparisons between studies. Nevertheless, all 31 studies consistently reported improvements in critical thinking skills. Sample sizes also varied, ranging from 10 students in an exploratory study (Ramli et al., 2025) to 678 students in a study with mediation analysis (Karademir & Soyulu, 2022).

Distributional Approach and Integration Categories

The 31 articles were classified into seven mutually exclusive integration categories based on the presence of four key components: PBL, STEAM/STEM, metacognitive strategies or prompts, and critical thinking skills. A study was assigned to a specific category if the listed components were employed as learning models or approaches and/or as research variables, whereas components designated as "absent" were not reported in the research design. A "full integration" category was designated when all four components were present simultaneously within a single study. These criteria were applied consistently to classify all articles and to prevent double-counting. The distribution of these categories is presented in detail in Table 6.

Table 6. Distribution of Integration Categories among the 31 Included Articles.

Integration Category	n	Percentage (%)
PBL + Critical Thinking (without STEAM, without metacognitive)	14	45,2
STEAM/STEM + Critical Thinking (without PBL, without metacognitive)	8	25,8
Metacognitive Strategies + CC (without PBL, without STEAM)	3	9,7
PBL + STEAM/STEM + CC (without metacognitive)	5	16,1
PBL + Metacognitive prompts + CC (without STEAM)	1	3,2
STEAM + Metacognitive prompts + CC	0	0,0
PBL + STEAM + Metacognitive prompts + CC (Full Integration)	0	0,0 GAP

Three main patterns can be identified from Table 6. First, PBL is the most frequently encountered component, appearing in 20 of the 31 studies (64.5%). Second, STEAM/STEM appears in 13 studies, yet most have not been combined with metacognitive strategies. Third, no studies were found that simultaneously integrate PBL, STEAM/STEM, and metacognitive prompts with critical thinking, indicating an integration gap in the analyzed literature.

Characteristics of Included Articles

Table 7 presents a complete list of the 31 articles included in the final synthesis. The articles are organized by variable integration categories and sorted chronologically within each category to facilitate analysis and comparison.

Table 7. Characteristics of the 31 Articles Included in the Final Synthesis.

Author	Year	Year Integration	Method	Level / n	Key Findings
Alkhabra et al.	2023	STEAM + AR	Experimental	Grade VIII / 120	AR-STEAM improved retention and CT.
Amanda et al.	2024	Complexity Science-Based PBL	Quasi-experimental	Biology students / 82	CS-PBL outperformed PBL and direct teaching.
Ananda et al.	2023	Design Thinking + STEAM-PjBL	Qualitative	Grade X / 41	Supported contextual problem solving and CT.
Ariyanti et al.	2024	Problem Mind Mapping-Based Learning	R&D + efficacy	Grade V / 10 trial; 3 x 30 field	Valid, practical, and effective for CT.
Casado Fernández & Checa-Romero	2023	STEAM Project-Based Learning	Ethnographic case study	Grades V-VI / 57	Strengthened creativity, teamwork, and CT.
Cintamulya et al.	2025	STEM-PBL + Literacy E-book	Descriptive exploratory	Biology students / 27; 10 focal	Supported CT, collaboration, communication, and literacy.
Dökmecioğlu et al.	2022	Constructivist Learning + Metacognitive Regulation	Cross-sectional mediation	Grade VII / 678	Learning environment and metacognition predicted CT dispositions.
Fernández-Cárdenas & Santillán-Rosas	2025	Dialogic STEAM	Mixed methods	Senior high / 100 + 10 teachers	Showed potential to improve CT.

Author	Year	Year Integration	Method	Level / n	Key Findings
Haris & Mahir	2025	Problem-Solving Physics	Quasi-experimental	Physics students / 60	Improved CT and self-directed learning.
Hastuti et al.	2024	Differentiated PBL	Quasi-experimental	Geography students / 68	Outperformed conventional learning in CT.
Küçük et al.	2023	Sustainable Progressive STEAM	Quasi-experimental	Grade V / 104	Improved CT dispositions and math achievement.
Langgi et al.	2025	PBL + Flipped Classroom	Quasi-experimental factorial	Vocational high / 62	Improved accounting CT across ability levels.
Lubna et al.	2023	Problem-Based Distance Learning in STEM	One-group pretest-posttest	STEM students / 28	Improved CT across cognitive styles.
Marthaliakirana et al.	2022	PBL + Metacognitive Prompts	Quasi-experimental	Grade XI / 121	Improved argumentation and CT beyond conventional PBL.
Nusantari et al.	2021	Discovery Learning + Metacognitive Knowledge	R&D + effectiveness	Students / 32 trial; 59 field	Valid, practical, and effective for CT.
Pereles et al.	2024	Online Metacognitive Strategies	Exploratory quasi-experimental	Master's students / 252	Improved CT in reflective reading, writing, and speaking.
Pertiwi et al.	2024	Contextual STEM-PBL + E-module + Virtual Experiment	4-D R&D + efficacy	Senior high / 216	More effective for CT than conventional media.
Pitorini et al.	2024	PBL + Socratic-Dialogue E-module	Quasi-experimental	Grade X / 144	Significantly improved CT.
Pitorini et al.	2025	PBL + Socratic-Dialogue E-module	Basic qualitative	Grade X / 10	CT aspects developed positively.
Putri et al.	2023	STEAM-Based Blended Learning	Quasi-experimental	Junior high / 180	Improved critical and creative thinking.
Qondias et al.	2022	Multicultural PBL	Quasi-experimental	Elementary / 165	Improved social attitudes and CT.
Ramli et al.	2024	PBL	Quasi-experimental	Pre-university / 48	Improved calculus achievement and mathematical CT.

Author	Year	Year Integration	Method	Level / n	Key Findings
Rizki & Suprpto	2024	Project-Oriented PBL + SR-STEM	Quasi-experimental	Senior high / 74	Fostered CT in renewable-energy learning.
Sari et al.	2025	STEAM	Quasi-experimental	School students / 126	Improved CT; arts enriched solution development.
Sha et al.	2021	STEAM Course	Within-subject experiment	Undergraduates / 30	Engagement level influenced CT performance.
Suhirman & Prayogi	2023	PBL + Mobile PhET Simulation	Randomized experiment	Islamic senior high / 88	Improved CT more than expository learning.
Sujanem & Suwindra	2023	Blended PBL + Physics E-module	One-group pretest-posttest	Grade XI / 79	Improved CT and received positive responses.
Susanto et al.	2022	PBL + E-book	ADDIE R&D + test	Grade V / 84	Improved CT in science learning.
Suyitno et al.	2024	PBL	Quasi-experimental	Grade X / 72	Improved CT over expository instruction.
Taningrum et al.	2024	PBL + Animated Video	One-group experiment	Grade XII / 32	Improved CT and learning outcomes.
Wilson et al.	2021	Transdisciplinary STEAM	Mixed-methods implementation	K-12 / 318	Fostered CT, creativity, problem solving, and collaboration.

Discussion

Research Trends and Context (RQ1)

The increase in publication frequency from 2021 to 2024 (from 9.7% to 32.3%) reflects a stronger global response to post-pandemic educational challenges. The COVID-19 disruption raised awareness of low critical thinking skills and encouraged the development of innovative learning models capable of maintaining meaningful learning, both in face-to-face and online contexts. Indonesia's dominance in the research corpus ($\pm 41.9\%$) is not merely coincidental but directly reflects the Independent Curriculum policy, which emphasizes the development of higher-order thinking skills through project-based and inquiry-based approaches. This policy alignment has also driven an increase in the number of empirical research in Indonesia, even surpassing some countries with comparable economic levels.

The dominance of research at the secondary school level (45%) also aligns theoretically, as PBL is more effective when applied to materials with sufficiently high cognitive demands, thus encouraging students' productive struggle (Suyitno et al., 2024). This situation is often found in secondary science topics such as thermodynamics, momentum and impulse, and renewable energy. Meanwhile, the relatively lower representation of research at the elementary school level does not indicate a mismatch in approaches, but rather indicates that the implementation of PBL and STEAM remains feasible and effective if adapted to student developmental characteristics, although it requires different learning design considerations.

Why PBL is Consistently Effective (RQ3)

The consistent effectiveness of PBL across all 20 studies in this corpus, including variations such as flipped classroom-based PBL (Sari et al., 2025), Socratic dialogue (Pitorini et al., 2024), blended e-modules (Sujanem & Suwindra, 2023), and integration with complexity science (Amalia et al., 2024), can be explained by its characteristic mechanisms that directly activate cognitive processes in critical thinking. The presentation of authentic, unstructured problems encourages the activation of prior knowledge and creates cognitive dissonance that triggers the investigative process. In the collaborative discussion phase, students are required to present, defend, and critically evaluate arguments in a social context, reflecting a form of external metacognitive regulation. Meanwhile, the investigation and evidence-gathering phase trains the ability to evaluate information and draw inferences, which align with the critical thinking indicators according to Facione (2011): analysis, inference, and evaluation.

Furthermore, variations of PBL supplemented with additional mechanisms such as Socratic questioning, animated media, or virtual simulations consistently demonstrate stronger results than PBL without such reinforcement. This suggests that scaffolding acts as a primary reinforcement in learning, not simply an additional element. These findings align with Vygotsky's Zone of Proximal Development theory, which emphasizes that learning support can expand students' problem-solving abilities, resulting in higher-quality critical thinking.

Interdisciplinary Dimension: STEAM as a Contextual Enhancer

The STEAM approach contributes to the development of critical thinking through a distinct mechanism, namely contextual complexity. When a problem requires the integration of various perspectives from science, technology, engineering, art, and mathematics, students are encouraged to engage in multi-perspective reasoning. This process directly trains interpretation (understanding a problem holistically) and explanation (providing justification based on various knowledge frameworks) skills, as indicators of critical thinking according to Facione. A transdisciplinary study by Wilson et al. (2021), involving 318 participants across seven states in the United States, showed that STEAM-based learning not only improves critical thinking skills but also simultaneously improves creative thinking a finding rarely reported in PBL studies focused on a single discipline. The stronger effect in middle school students compared to elementary school students also aligns with cognitive development theory, where cross-domain abstract thinking skills develop more optimally at the formal operational stage. Furthermore, the findings of Küçük et al. (2023) provides important implications for learning design, namely that the continuous implementation of STEAM is more effective than a one-time implementation. The SP-STEAM program, conducted over four cycles, was shown to significantly improve critical thinking dispositions and mathematics achievement compared to a single-session intervention. Furthermore, research by Alkhabra et al. (2023) integrating augmented reality technology into STEAM demonstrates that the complexity of learning design needs to be balanced with the management of students' cognitive load. Therefore, the use of appropriate scaffolding is crucial to ensure that the cognitive challenges provided remain productive and do not exceed students' working memory capacity.

Metacognitive Dimension: The Regulatory Multiplier Effect

Although the number of metacognitive studies in this corpus is relatively small ($n = 4$), the findings have significant theoretical implications. The study by Marthaliakirana et al. (2022) is among the most relevant because it provides empirical evidence of a synergistic, rather than simply additive, relationship between metacognitive prompts and PBL. In this study, metacognitive prompts encouraged students to explain their thinking strategies, identify gaps in understanding, and evaluate the quality of arguments at each stage of the PBL cycle. These improved results compared to conventional PBL demonstrate that metacognitive scaffolding not only improves the quantity of cognitive engagement but also the quality of students' thinking processes.

Furthermore, a mediation analysis by Karademir and Soylu (2022) provided a structural explanation for these findings, namely that metacognitive self-regulation strategies not only correlate with critical thinking but also act as a mediator, bridging the constructivist learning environment with the development of critical thinking dispositions. This suggests that without explicit metacognitive mechanisms, even well-designed PBL or STEAM-based learning may not optimize the development of

Patterns and Gaps... (Maharani & Parno) pp:382-397

critical thinking. Furthermore, the findings of Pereles et al. (2024) demonstrating the effectiveness of metacognitive strategies in enhancing critical thinking in the context of online learning in higher education extend the relevance of this approach beyond face-to-face learning in schools.

Integration Patterns and Key Research Gaps

An analysis of the integration matrix between components in 31 articles revealed systematic and significant fragmentation. PBL was largely studied as a single approach, while STEAM was generally studied separately without a PBL pedagogical framework. Metacognitive prompts, theoretically considered to have the greatest potential for reinforcement, appeared in only one study in combination with PBL and were not found in the integration with STEAM.

This fragmentation reflects more than just a bibliometric pattern; it represents a scientific gap with practical implications. Theoretically, an integration framework for the three components is readily available and complementary. Vygotsky's constructivist theory forms the basis for the problem-based learning structure in PBL, interdisciplinary educational theory supports the role of STEAM in enriching the learning context, while metacognition theory (Flavell, 1979) and self-regulated learning (Zimmerman, 2000) provide the basis for the use of metacognitive strategies as mechanisms for regulating thinking. These three approaches are not only compatible but also complementary: PBL without metacognitive support provides insufficient guidance for thinking regulation, STEAM without a PBL structure lacks systematic implementation, and metacognitive strategies without an interdisciplinary context lack optimal cognitive challenge.

The lack of an empirically validated integrated learning model is a crucial issue, especially in the Indonesian context. This is because the Independent Curriculum explicitly demands integrated learning oriented toward competency development. However, in practice, teachers still lack an operational, evidence-based learning model for implementation. Therefore, the development and empirical testing of an integrated PBL–STEAM–metacognitive prompts model is an urgent need, both from a theoretical perspective and in educational practice.

Methodological Considerations and Limitations

The predominant use of quasi-experimental designs (51,6%) with unequal control groups has the potential to introduce bias due to initial differences between groups, which could influence the estimation of treatment effects. Only a small number of studies employed full randomization. Furthermore, the variety of critical thinking measurement instruments used in various studies limits meta-analyses and accurate quantitative comparisons between studies. A search strategy that uses only one database, Scopus, also potentially overlooks relevant articles indexed in other databases such as Web of Science, ERIC, or PsycINFO. The restriction to English-language articles and indexed journals excludes Indonesian-language publications and grey literature. Furthermore, the publication window of 2021–2026, while ensuring the freshness of the literature, excludes previous studies that could have made important contributions to the development of the current theoretical framework.

CONCLUSION

This systematic literature review analyzed 31 empirical articles selected from an initial pool of 188 using the PRISMA 2020 framework. Regarding RQ1, publications concerning PBL, STEAM/STEM, metacognitive strategies, and critical thinking increased during 2021–2024; Indonesia was the largest contributor (41.9%), and secondary education was the dominant context. PBL was the most frequently identified component, followed by STEAM/STEM and metacognitive strategies. Regarding RQ2, quasi-experimental designs predominated (51.6%), alongside experimental, qualitative, mixed-methods, and developmental studies incorporating effectiveness testing. The variety of critical thinking measurement instruments indicates differences in construct operationalization, limiting direct quantitative comparisons across studies; nevertheless, most studies reported improvements in critical thinking following the implementation of the approaches examined. Regarding RQ3, PBL, STEAM/STEM, and metacognitive strategies contribute to critical thinking through complementary mechanisms: PBL promotes inquiry and problem-solving, STEAM/STEM provides interdisciplinary learning contexts, and metacognitive strategies support the planning, monitoring, and

evaluation of thinking processes. Although some studies demonstrated the benefits of partial combinations, particularly PBL with metacognitive prompts, the simultaneous integration of all three components was not identified in the analyzed literature.

Regarding RQ4, the review reveals a clear integration gap: none of the 31 studies simultaneously integrated PBL, STEAM/STEM, and metacognitive prompts within a single instructional design targeting critical thinking. Existing research therefore remains fragmented, focusing primarily on individual components or partial combinations. This finding provides empirical justification for developing and testing an integrated PBL–STEAM learning model supported by metacognitive prompts, particularly in secondary science and physics education. Future research should examine whether such full integration can enhance students' critical thinking and test its effectiveness across diverse educational contexts to establish the model's broader applicability.

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