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Scientific literacy outcomes of STEM-integrated problem-oriented project-based learning among indonesian eighth-grade students: A quasi-experimental study

Arini Rahma Dhani*
Universitas Nusa Cendana, INDONESIA

Ulil Hac D
Universitas Nusa Cendana, INDONESIA

Familia Claudia Awil
Universitas Nusa Cendana, INDONESIA

Christin Cisiliya Bentura
Universitas Nusa Cendana, INDONESIA

Hendrikus Moan Liwu
Universitas Nusa Cendana, INDONESIA

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Abstract

Background: Scientific literacy development remains challenging in Indonesian junior high schools, particularly when students have limited opportunities to investigate scientific phenomena and apply knowledge to contextual problems. Preliminary observations in Kupang revealed difficulties in interpreting scientific information and connecting concepts with everyday situations.
Aims: This study examined scientific literacy outcomes associated with STEM-integrated Problem-Oriented Project-Based Learning (POPBL) among Indonesian eighth-grade students.
Method: A quasi-experimental nonequivalent pretest–posttest control group design involved 104 eighth-grade students from two junior high schools in Kupang, Indonesia. Scientific literacy was assessed using eight expert-validated essay items covering four competency indicators. Descriptive statistics and an independent-samples t-test were employed to examine posttest differences.
Results: The experimental group's mean score increased from 52.16 to 66.35, whereas the control group's mean decreased from 53.37 to 46.21. The posttest difference was statistically significant, $t(102) = 4.374$, $p < .001$, favoring STEM-integrated POPBL.
Conclusion: STEM-integrated POPBL was associated with higher scientific literacy outcomes, suggesting its potential for supporting interdisciplinary science education. Further baseline-adjusted analyses are needed to strengthen causal interpretation.

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INTRODUCTION

Scientific literacy constitutes a multidimensional competency that enables students to interpret scientific evidence, explain natural phenomena, evaluate scientific information, and apply scientific knowledge to real-world problems. Contemporary science education emphasizes that scientific literacy extends beyond conceptual mastery to encompass scientific reasoning, investigative practices, and informed decision-making within complex social and technological environments (Ke et al., 2021; Li & Guo, 2021; O'Toole et al., 2020). The Organisation for Economic Co-operation and Development conceptualizes scientific literacy through competencies involving scientific explanation, evaluation of scientific inquiry, and interpretation of scientific data and evidence. These competencies are particularly relevant to junior high school education, where

***Corresponding author:**
Arini Rahma Dhani, Universitas Nusa Cendana, Indonesia
arini.rahma.dhani@staf.undana.ac.id

students progressively develop the ability to connect scientific concepts with observable phenomena and contextual problems. Research on scientific modelling suggests that engaging students in constructing and evaluating representations of scientific phenomena can support meaningful participation in scientific reasoning (Ke et al., 2021). Similarly, guided inquiry supported by digital simulations has been investigated as an instructional approach associated with science achievement and scientific literacy development (Wen et al., 2020). Studies addressing socioscientific issues further emphasize the importance of connecting scientific knowledge with evidence-based argumentation, communication, and contextual decision-making (Li & Guo, 2021). Nevertheless, the development of scientific literacy depends not only on the acquisition of scientific knowledge but also on opportunities to apply that knowledge through investigation, interpretation, and problem-solving activities. This perspective highlights the importance of instructional environments that integrate conceptual understanding with authentic scientific practices rather than emphasizing factual memorization alone. Accordingly, identifying learning approaches that support multiple dimensions of scientific literacy remains a significant priority in contemporary science education, particularly within educational systems experiencing persistent disparities in scientific achievement.

The development of scientific literacy remains a substantial educational concern in Indonesia, as reflected in international assessments of students' scientific competencies. According to the Indonesian students obtained an average science score of 383 in PISA 2022, substantially below the OECD average of 485. Furthermore, only 34% of Indonesian students achieved at least Level 2 proficiency in science, compared with 76% across OECD countries, indicating considerable challenges in demonstrating foundational scientific competencies. These findings suggest that many Indonesian students experience difficulties recognizing scientific explanations, interpreting evidence, and evaluating conclusions derived from scientific information. The more recent PISA 2025 assessment reported that approximately 37% of Indonesian students attained Level 2 proficiency or higher in science, indicating that substantial proficiency challenges persisted. At the regional level, educational challenges in East Nusa Tenggara have been discussed in relation to students' learning motivation, critical thinking, self-confidence, instructional practices, and access to educational resources (Suri et al., 2025). However, these characteristics should be interpreted as potentially associated factors rather than established determinants of scientific literacy without supporting causal evidence. Preliminary classroom observations at SMP Negeri 3 Kota Kupang and SMPK Muder Teresa Kota Kupang also suggested that some eighth-grade students experienced difficulties interpreting contextual scientific problems and connecting scientific concepts with everyday situations. Although these observations provided an initial basis for investigating instructional alternatives, their exploratory nature does not establish the prevalence or magnitude of scientific literacy difficulties within the participating schools. Consequently, the combination of national assessment evidence and local instructional concerns underscores the importance of examining learning approaches that provide structured opportunities for scientific investigation, evidence interpretation, and contextual knowledge application.

Integrated Science, Technology, Engineering, and Mathematics (STEM) education and Project-Oriented Problem-Based Learning (POPBL) offer complementary instructional perspectives for organizing science learning around authentic problems and interdisciplinary applications. Integrated STEM education emphasizes meaningful connections among scientific concepts, technological applications, engineering practices, and mathematical reasoning rather than treating these disciplines as independent areas of knowledge (Ortiz-Revilla et al., 2022; Roehrig et al., 2021). Conceptual frameworks developed by Cheng and So (2020) and Roehrig et al. (2021) further indicate that the educational value of STEM integration depends on how disciplinary relationships are established within instructional activities. Empirical investigations have examined integrated STEM curricula in relation to science learning, cognitive performance, and broader educational outcomes,

suggesting that interdisciplinary approaches can provide productive contexts for student learning (Anwar et al., 2022; Le et al., 2023). Meanwhile, POPBL combines the problem-centered inquiry characteristic of Problem-Based Learning with the sustained investigation and project development commonly associated with Project-Based Learning, thereby linking problem identification with the production and evaluation of proposed solutions (Servant-Miklos, 2020). Previous studies have explored POPBL in interdisciplinary learning environments and reported outcomes related to creativity, critical thinking, and twenty-first-century competencies (Alali, 2024; Chang et al., 2022; Rizki & Suprapto, 2024). These investigations demonstrate that integrating STEM with POPBL is not entirely new, making it necessary to distinguish the present study from existing research through its specific learning outcomes, educational context, and assessment framework. Furthermore, scientific literacy studies have investigated approaches involving guided inquiry, scientific modelling, and contextualized socioscientific issues, although their instructional characteristics differ from those of STEM-integrated POPBL (Wen et al., 2020; Ke et al., 2021; Li & Guo, 2021). Despite these contributions, the relationship between STEM-integrated POPBL and scientific literacy outcomes across multiple competency indicators among Indonesian eighth-grade students remains insufficiently established within the literature examined, particularly in relation to identifying scientific phenomena, interpreting evidence, understanding scientific concepts, and applying scientific knowledge. Therefore, a context-specific empirical investigation is warranted to examine scientific literacy outcomes associated with STEM-integrated POPBL and to extend existing evidence concerning interdisciplinary instructional approaches in junior high school science education.

Previous studies have highlighted the potential of integrated Science, Technology, Engineering, and Mathematics (STEM) education and Project-Oriented Problem-Based Learning (POPBL) to enhance students' cognitive performance, creativity, critical thinking, and twenty-first-century competencies across diverse educational contexts (Chang et al., 2022; Rizki & Suprapto, 2024). Existing theoretical frameworks and empirical investigations have further emphasized the importance of interdisciplinary integration, authentic problem-solving, and project-based activities in supporting meaningful STEM learning experiences (Roehrig et al., 2021; Ortiz-Revilla et al., 2022; Anwar et al., 2022; Le et al., 2023). Meanwhile, scientific literacy research has explored various instructional approaches, including scientific modelling, guided inquiry, and contextualized socio-scientific issues, to strengthen students' understanding and application of scientific knowledge (Wen et al., 2020; Ke et al., 2021; Li & Guo, 2021). Although these studies provide valuable insights into STEM integration and scientific literacy development, the extent to which STEM-integrated POPBL is associated with scientific literacy outcomes across multiple competency indicators among Indonesian junior high school students remains insufficiently established within the literature examined. Furthermore, previous investigations have addressed diverse learning outcomes and educational settings, highlighting the importance of context-specific evaluations that distinguish scientific literacy from broader cognitive and twenty-first-century competencies (Anwar et al., 2022; Le et al., 2023; Ali, 2024; Rizki & Suprapto, 2024). Addressing this gap, the present study examines scientific literacy outcomes among Indonesian eighth-grade students participating in STEM-integrated POPBL through a quasi-experimental pretest–posttest design, focusing on four indicators: identifying scientific problems, interpreting data and drawing conclusions, understanding scientific concepts, and applying scientific knowledge to everyday situations. By providing comparative evidence from two junior high schools in Kupang, Indonesia, this study contributes to the empirical understanding of interdisciplinary STEM instruction and its relationship with scientific literacy development in secondary science education.

Building upon the identified research gap, this study aimed to examine scientific literacy outcomes associated with STEM-integrated Project-Oriented Problem-Based Learning (POPBL) among Indonesian eighth-grade students. Specifically, the investigation sought to compare scientific

literacy performance between students participating in STEM-integrated POPBL and those receiving comparison instruction in two junior high schools in Kupang, East Nusa Tenggara, Indonesia. The study employed a quasi-experimental nonequivalent pretest–posttest control group design to investigate differences in scientific literacy outcomes across instructional conditions. Scientific literacy was operationalized through four competency indicators: identifying scientific problems or phenomena, interpreting data and drawing conclusions, understanding scientific concepts, and applying scientific knowledge in everyday situations. The first research objective was to describe students' scientific literacy performance before and after the instructional intervention in both experimental and control groups. The second objective was to determine whether students participating in STEM-integrated POPBL demonstrated significantly different posttest scientific literacy outcomes compared with students receiving comparison instruction. Accordingly, the research hypothesis proposed that students exposed to STEM-integrated POPBL would demonstrate higher posttest scientific literacy scores than those in the control group, while recognizing that the nonequivalent group design limits causal interpretation. The distinctive empirical contribution of this investigation lies in examining scientific literacy as a multidimensional learning outcome within an interdisciplinary instructional approach that integrates scientific inquiry, contextual problem-solving, and project development. By focusing on eighth-grade students in the Indonesian educational context, the study seeks to extend empirical understanding of STEM-integrated POPBL implementation and its relationship with scientific literacy competencies in junior high school science education. Ultimately, the findings are expected to provide context-specific comparative evidence that may inform the evaluation and refinement of interdisciplinary, problem-oriented project-based instruction for supporting scientific literacy development.

LITERATURE REVIEW

Scientific literacy has increasingly been conceptualized as a multidimensional competency that integrates scientific knowledge, inquiry practices, evidence-based reasoning, and the application of scientific understanding to everyday situations. Contemporary perspectives emphasize that scientifically literate individuals should be capable of interpreting scientific information, evaluating the credibility of evidence, and constructing explanations that account for observable phenomena (O'Toole et al., 2020; Li & Guo, 2021). The development of these competencies requires learning experiences that extend beyond factual acquisition and encourage students to engage actively in scientific investigation and knowledge construction. Ke et al. (2021) highlighted the educational relevance of scientific modelling in helping students develop and use representations to understand complex scientific phenomena within socioscientific contexts. Similarly, Wen et al. (2020) investigated the relationship between simulation-supported guided inquiry, science achievement, and scientific literacy, illustrating the relevance of inquiry-oriented learning environments to scientific competency development. These perspectives suggest that scientific literacy involves interconnected cognitive processes through which students identify scientific problems, interpret evidence, construct explanations, and evaluate possible solutions. Nevertheless, scientific literacy should not be treated as interchangeable with general academic achievement because its assessment requires explicit consideration of scientific reasoning and knowledge application. In junior high school science education, these competencies are particularly important because students are transitioning toward increasingly abstract scientific concepts and more complex investigative activities (Alkhabra et al., 2023; Morris, 2025). Accordingly, scientific literacy assessment should incorporate indicators that represent conceptual understanding alongside the ability to interpret scientific information and apply knowledge in contextual situations. Within this conceptual

framework, the present study examines scientific literacy through four indicators: identifying scientific problems or phenomena, interpreting data and drawing conclusions, understanding scientific concepts, and applying scientific knowledge to everyday situations.

Integrated Science, Technology, Engineering, and Mathematics (STEM) education represents an interdisciplinary instructional approach that connects disciplinary knowledge and practices through authentic problems requiring coordinated scientific and technological reasoning. Rather than presenting STEM disciplines as independent subjects, integrated STEM education encourages students to recognize conceptual relationships among scientific principles, technological applications, engineering design, and mathematical representations (Roehrig et al., 2021; Ortiz-Revilla et al., 2022). Cheng and So (2020) emphasized that STEM integration can be organized through different instructional models, indicating that the depth and structure of disciplinary connections influence how interdisciplinary learning is implemented (Cheng & So, 2020). Roehrig et al. (2021) further proposed a conceptual framework highlighting authentic problems, engineering design, contextual integration, disciplinary content, and STEM practices as important characteristics of integrated STEM instruction. These theoretical perspectives suggest that meaningful STEM integration requires more than incorporating activities associated with multiple disciplines into a single lesson. Empirical investigations have examined integrated STEM curricula in relation to students' science learning and cognitive performance, providing evidence that interdisciplinary instruction can support different educational outcomes depending on its implementation (Anwar et al., 2022). Furthermore, Le et al. (2023) synthesized 47 studies involving K–12 STEM education and identified variations in learning outcomes across different approaches to interdisciplinary integration. Their findings indicate that project-based STEM activities within school curricula have frequently been associated with academic achievement and higher-order thinking skills, whereas extracurricular approaches have often emphasized STEM-related interests and career aspirations. However, the diversity of instructional models and assessment objectives makes it difficult to generalize findings across educational contexts without considering the characteristics of individual interventions. Consequently, examining STEM integration within a clearly defined instructional framework is necessary to understand its relationship with specific scientific literacy competencies among junior high school students.

Project-Oriented Problem-Based Learning (POPBL) combines problem-centered inquiry with sustained project development to organize learning activities around authentic challenges requiring investigation, collaboration, and the application of disciplinary knowledge. Conceptually, this approach draws on characteristics of Problem-Based Learning (PBL), which emphasizes inquiry initiated by complex problems, and Project-Based Learning (PjBL), which organizes learning through extended activities directed toward meaningful project outcomes (Sánchez-García & Reyes-de-Cózar, 2025). Servant-Miklos (2020) distinguished problem-oriented project work from conventional problem-based learning traditions, demonstrating that these approaches differ in their historical development, instructional organization, and underlying educational principles. This distinction is important because POPBL should be understood as an instructional framework with identifiable learning processes rather than a simple combination of two interchangeable pedagogical labels. Within POPBL, students are expected to examine contextual problems, formulate possible explanations, gather relevant information, develop project-based solutions, and communicate their findings through collaborative activities. Such learning processes may provide opportunities for students to connect conceptual knowledge with investigative practices while developing their ability to justify decisions using scientific evidence (Gizaw & Sota, 2023; Manz et al., 2020). Chang et al. (2022) investigated interdisciplinary POPBL in relation to student creativity, suggesting the relevance of project-oriented inquiry to learning outcomes beyond conventional knowledge acquisition. Similarly, examined integrated STEM education using POPBL in relation to twenty-first-

century competencies, while Rizki and Suprapto (2024) investigated POPBL through an SR-STEM approach focusing on students' critical thinking in renewable energy learning. Although these studies demonstrate the applicability of POPBL across different educational contexts, their respective emphases on creativity, critical thinking, and broader competencies do not directly establish its relationship with every dimension of scientific literacy. Therefore, further investigation is warranted to examine how STEM-integrated POPBL is associated with students' abilities to identify scientific phenomena, interpret evidence, understand scientific concepts, and apply scientific knowledge in everyday situations.

The integration of STEM education with POPBL provides a pedagogical framework in which scientific inquiry and interdisciplinary problem-solving can be organized through collaborative project activities. From a conceptual perspective, STEM integration contributes disciplinary connections and authentic applications, whereas POPBL structures the learning process through problem identification, investigation, project development, and evaluation (Servant-Miklos, 2020; Roehrig et al., 2021). These complementary characteristics may create opportunities for students to investigate scientific phenomena while considering technological possibilities, engineering constraints, and mathematical evidence. For example, identifying contextual problems can encourage students to formulate scientific questions, while project implementation can require them to interpret information and apply scientific concepts to proposed solutions. The presentation and evaluation of project outcomes may also provide opportunities for students to communicate scientific explanations and justify conclusions through evidence-based reasoning. Previous investigations have associated integrated STEM instruction with science learning and cognitive performance, although the observed outcomes vary according to instructional design and educational context (Anwar et al., 2022; De Loof et al., 2022; Le et al., 2023). Meanwhile, studies involving STEM-related POPBL have examined critical thinking and twenty-first-century competencies, suggesting that the approach has potential relevance to broader scientific reasoning processes (Rizki & Suprapto, 2024). Nevertheless, improvements in critical thinking or general academic performance cannot automatically be interpreted as improvements in scientific literacy because these constructs involve overlapping but distinguishable competencies. Establishing the relationship between STEM-integrated POPBL and scientific literacy therefore requires assessment instruments that explicitly measure scientific problem identification, evidence interpretation, conceptual understanding, and contextual knowledge application. Accordingly, the theoretical relationship between interdisciplinary project-oriented instruction and scientific literacy provides a rationale for empirical investigation without presupposing that the intervention necessarily produces superior learning outcomes.

Existing research provides substantial theoretical and empirical support for integrated STEM education and project-oriented learning, although the reported outcomes vary across instructional approaches, educational levels, and assessment frameworks (Roehrig et al., 2021; Anwar et al., 2022; Le et al., 2023). A systematic review by Le et al. (2023) demonstrated that different forms of integrated STEM instruction are associated with distinct learning outcomes, reinforcing the importance of evaluating specific instructional designs rather than treating STEM integration as a uniform intervention. Studies involving POPBL have similarly investigated creativity, critical thinking, and twenty-first-century competencies, providing relevant evidence while leaving room for further examination of scientific literacy as a multidimensional learning outcome (Chang et al., 2022; Rizki & Suprapto, 2024). In parallel, scientific literacy investigations have explored guided inquiry, scientific modelling, and socioscientific learning contexts, highlighting the diversity of pedagogical approaches through which scientific reasoning can be examined (Wen et al., 2020; Ke et al., 2021; Li & Guo, 2021). However, the literature considered in this review does not sufficiently establish how STEM-integrated POPBL is associated with scientific literacy outcomes across multiple competency

indicators among Indonesian eighth-grade students. This limitation represents a context-specific empirical gap rather than evidence that STEM-integrated POPBL or scientific literacy interventions have not previously been investigated. Furthermore, differences in instructional conditions and assessment practices across previous studies underscore the importance of clearly operationalizing scientific literacy and specifying the characteristics of the learning intervention. A quasi-experimental pretest–posttest design offers a means of examining scientific literacy performance across instructional conditions, although nonequivalent group allocation requires caution when interpreting observed differences (Al-Ghafiriya et al., 2026; Bach & Le, 2026; Chengere et al., 2026). By examining four scientific literacy indicators among eighth-grade students in Kupang, Indonesia, the present study seeks to extend existing evidence concerning the relationship between interdisciplinary STEM instruction and scientific literacy development. Its principal contribution lies in providing context-specific comparative evidence on scientific literacy outcomes associated with STEM-integrated POPBL, thereby informing further research on instructional design and competency-oriented assessment in junior high school science education.

METHOD

Research Design

This study employed a quantitative approach using a quasi-experimental nonequivalent pretest–posttest control group design to examine scientific literacy outcomes associated with STEM-integrated Project-Oriented Problem-Based Learning (POPBL). This design was appropriate for investigating instructional differences in existing classroom settings where individual random assignment was not implemented. The study involved an experimental group receiving STEM-integrated POPBL instruction and a control group participating in conventional science instruction. Both groups completed scientific literacy assessments before and after the instructional intervention to document their initial performance and subsequent learning outcomes. The pretest was administered to identify students' baseline scientific literacy competencies, whereas the posttest was conducted to evaluate their performance following the respective instructional conditions. The experimental intervention integrated scientific inquiry, contextual problem-solving, interdisciplinary STEM applications, and project development within a structured learning process. Meanwhile, the control group participated in conventional science instruction without the specific integration of POPBL and STEM activities implemented in the experimental condition. The use of existing classroom groups allowed the investigation to be conducted within authentic educational settings while maintaining the instructional arrangements of the participating schools. Nevertheless, the nonequivalent group design may introduce potential selection bias and baseline differences that should be considered when interpreting the findings. The experimental design is presented in Table 1.

Table 1. Nonequivalent Pretest–Posttest Control Group Design

Group	Pretest	Treatment	Posttest
Experimental	O_1	X_1	O_2
Control	O_3	X_2	O_4

Participants

The participants consisted of 104 eighth-grade students enrolled at SMP Negeri 3 Kota Kupang and SMPK Muder Teresa Kota Kupang, East Nusa Tenggara, Indonesia. These schools were selected using purposive sampling to establish the educational settings for investigating scientific literacy outcomes associated with STEM-integrated POPBL. The study involved students from Grade VIII classes, including Classes VIII A and VIII B, which served as the classroom groups participating

in the investigation. The original sampling procedure involved random selection and allocation of classroom groups to experimental and control instructional conditions. Accordingly, the experimental group participated in STEM-integrated POPBL instruction, whereas the control group received conventional science instruction. The use of existing classroom groups was intended to accommodate regular school learning arrangements and minimize disruption to instructional activities. Both groups participated in scientific literacy assessments using the same assessment framework to support comparisons across instructional conditions. The selection of two schools provided an opportunity to investigate the instructional approach within the junior high school educational context of Kupang. However, potential differences in school characteristics, classroom environments, and students' initial competencies may have influenced the observed learning outcomes. Therefore, the findings were interpreted within the context of the participating schools, acknowledging the limitations associated with purposive school selection and classroom-based group allocation.

Research Instruments and Data Collection

The study employed instructional materials and a scientific literacy assessment instrument to support the implementation and evaluation of the learning intervention. The instructional materials consisted of teaching modules, learning media, and student worksheets designed to facilitate learning activities in accordance with the instructional conditions. Scientific literacy was measured using a written assessment comprising eight essay questions developed to evaluate students' understanding and application of scientific knowledge. The assessment covered four scientific literacy indicators: identifying scientific problems or phenomena, interpreting data and drawing conclusions, understanding scientific concepts, and applying scientific concepts in everyday situations. These indicators were adapted from the scientific literacy assessment framework referenced by Gormally et al. (2012), emphasizing scientific reasoning, evidence interpretation, and the application of scientific knowledge. Each essay question was assessed using a four-point scoring rubric, with scores ranging from 1 to 4 according to the quality of students' responses. The essay format allowed students to demonstrate their scientific understanding through explanations, interpretations, and reasoning rather than relying exclusively on selected-response answers. Before administration, the assessment instrument underwent expert validation and testing to evaluate its suitability for measuring the intended scientific literacy competencies. The assessment was administered to both groups before and after the instructional intervention to obtain pretest and posttest data. Students' responses were subsequently scored using the established assessment rubric, and the resulting scores were compiled for descriptive and inferential statistical analyses.

Data Analysis

The collected data were analyzed using descriptive and inferential statistical procedures to examine differences in scientific literacy outcomes between the experimental and control groups. Descriptive analysis was conducted to summarize students' pretest and posttest scores and describe changes in scientific literacy performance across the instructional period. Mean scores were calculated for both groups to provide an overview of their scientific literacy performance before and after the respective instructional conditions. The analysis also considered the four scientific literacy indicators to describe students' performance across different dimensions of scientific competency. Before hypothesis testing, statistical assumptions were examined through normality and homogeneity tests to determine the suitability of the selected parametric analysis. The homogeneity of variance assumption was evaluated using Levene's test, with significance values greater than 0.05 interpreted as indicating insufficient evidence against the assumption of equal variances. An independent-samples *t*-test was subsequently employed to compare posttest scientific literacy scores between the experimental and control groups. The null hypothesis stated that there was no

difference in mean posttest scientific literacy scores between the two groups, whereas the alternative hypothesis proposed that a difference existed. Statistical significance was determined using a two-tailed significance level of 0.05, with the null hypothesis rejected when $p < 0.05$ and not rejected when $p \geq 0.05$. All statistical analyses were performed using SPSS version 20, and the findings were interpreted with consideration of the nonequivalent group design and the limitations of posttest comparisons in establishing causal relationships. Students' scientific literacy performance was also interpreted descriptively using the score classification presented in Table 2. These categories were used to describe achievement levels rather than to determine statistical significance.

Table 2. Categories of Students' Scientific Literacy Abilities

No.	Score Range	Category
1	80–100	Very High
2	66–79	High
3	56–65	Moderate
4	40–55	Low
5	0–39	Very Low

Research Procedure

The research procedure consisted of preparation, pretest administration, instructional implementation, posttest administration, and data analysis. During the preparation stage, the researchers developed instructional materials and scientific literacy assessment instruments appropriate to the learning objectives and characteristics of eighth-grade science education. The instructional materials included teaching modules, learning media, and student worksheets designed to support the implementation of STEM-integrated POPBL activities. Before the instructional intervention, students in the experimental and control groups completed a scientific literacy pretest to document their initial competencies. Following the pretest, the experimental group participated in STEM-integrated POPBL instruction organized around four principal stages: problem orientation and formulation, organization of learning activities, project design and implementation, and presentation and evaluation. During the initial stage, students were introduced to contextual scientific problems and encouraged to identify relevant phenomena and formulate questions requiring scientific investigation. The subsequent stages involved organizing collaborative learning activities, designing and implementing projects, and applying scientific knowledge alongside relevant technological, engineering, and mathematical considerations. Students then presented their project outcomes and participated in evaluation activities involving scientific explanations, interpretation of information, and discussion of proposed solutions. Meanwhile, the control group participated in conventional science instruction covering the learning content addressed during the instructional period. After the completion of the instructional activities, both groups completed the scientific literacy posttest, and the assessment results were compiled and analyzed to examine differences in scientific literacy outcomes between the two instructional conditions.

RESULTS AND DISCUSSION

Results

The descriptive findings revealed different patterns of scientific literacy performance between students participating in STEM-integrated Project-Oriented Problem-Based Learning (POPBL) and those receiving conventional science instruction. As presented in Table 3, the experimental group demonstrated an increase in its overall mean scientific literacy score from 52.16 at pretest to 66.35 at posttest, representing a descriptive improvement of 14.19 points. Conversely, the control group exhibited a decrease from 53.37 to 46.21, corresponding to a reduction of 7.16

points. The difference between the groups' mean pretest scores was relatively small, with the control group scoring 1.21 points higher than the experimental group. Following the instructional period, the experimental group's mean posttest score exceeded that of the control group by 20.14 points. The difference between the two groups' descriptive score changes was 21.35 points, indicating contrasting patterns of performance across the instructional conditions. These findings suggest that the experimental group experienced more favorable changes in scientific literacy scores during the study period. However, these descriptive differences should not be interpreted as definitive evidence of instructional effectiveness without considering score variability, baseline characteristics, and potential differences between the participating groups. The detailed results for each scientific literacy indicator are presented in Table 3.

Table 3. Mean Pretest and Posttest Scientific Literacy Scores in the Experimental and Control Groups

Scientific Literacy Indicators	Assessment Period	Experimental Group (STEM-Integrated POPBL)	Control Group
Identifying scientific problems or phenomena	Pretest	12.26	13.34
	Posttest	16.83	12.02
Interpreting data and drawing conclusions	Pretest	13.82	13.52
	Posttest	16.59	11.06
Understanding scientific concepts	Pretest	13.70	13.76
	Posttest	16.41	11.48
Applying scientific concepts in everyday life	Pretest	12.38	12.74
	Posttest	16.53	11.66
Overall Scientific Literacy Score	**Pretest**	**52.16**	**53.37**
	Posttest	**66.35**	**46.21**
Scientific Literacy Category	**Pretest**	**Low**	**Low**
	Posttest	**High**	**Low**

A closer examination of the indicator-level results revealed that the experimental group demonstrated positive descriptive changes across all four scientific literacy indicators. The largest improvement occurred in identifying scientific problems or phenomena, with the mean score increasing from 12.26 to 16.83, representing a gain of 4.57 points. Applying scientific concepts in everyday life showed the second-largest improvement, increasing from 12.38 to 16.53, corresponding to a gain of 4.15 points. Meanwhile, interpreting data and drawing conclusions increased from 13.82 to 16.59, representing an improvement of 2.77 points. Understanding scientific concepts exhibited a similar pattern, increasing from 13.70 to 16.41, with a gain of 2.71 points. These findings indicate that the most pronounced descriptive improvements were observed in scientific problem identification and contextual knowledge application. In contrast, the control group demonstrated decreases across all four indicators, with the largest reduction occurring in interpreting data and drawing conclusions, from 13.52 to 11.06. Understanding scientific concepts also decreased from 13.76 to 11.48, while identifying scientific problems and applying scientific concepts declined by 1.32 and 1.08 points, respectively. Although these patterns provide useful information about students' performance across scientific literacy competencies, the absence of indicator-specific inferential tests prevents conclusions about the statistical significance of individual indicator changes.

Table 4. Descriptive Changes in Scientific Literacy Scores Across Instructional Conditions

Scientific Literacy Indicators	Experimental Group Change	Control Group Change	Difference in Changes
Identifying scientific problems or phenomena	+4.57	−1.32	+5.89
Interpreting data and drawing conclusions	+2.77	−2.46	+5.23
Understanding scientific concepts	+2.71	−2.28	+4.99

Applying scientific concepts in everyday life	+4.15	−1.08	+5.23
Overall Scientific Literacy Score	**+14.19**	**−7.16**	**+21.35**

Before conducting the inferential analysis, statistical assumption testing was performed to examine the distributional characteristics and variance homogeneity of the scientific literacy scores. The reported normality test produced significance values of 0.076 for pretest scores and 0.053 for posttest scores, both exceeding the conventional threshold of 0.05. These results indicated that the tests did not detect statistically significant departures from normality in the distributions examined. The reported homogeneity tests also produced significance values greater than 0.05, suggesting insufficient evidence to reject the assumption of equal variances. However, the original statistical output did not identify the specific normality test or provide separate normality results for each instructional group. Consequently, the available results should be interpreted cautiously because the assumption of normality for the relevant group-level distributions cannot be fully evaluated from the reported information alone. The available assumption-testing results are summarized in Table 5.

Table 5. Reported Normality and Homogeneity Test Results

Statistical Assumption	Pretest (*p*)	Posttest (*p*)	Interpretation
Normality	0.076	0.053	No statistically significant departure from normality detected
Homogeneity of variance	0.052	0.525	No statistically significant variance inequality detected

The independent-samples *t*-test was conducted to examine differences in posttest scientific literacy scores between the experimental and control groups. As presented in Table 6, Levene's test for equality of variances produced $F = 0.660$ and $p = 0.418$, indicating insufficient evidence to reject the equal-variance assumption for the posttest comparison. Under the equal-variance assumption, the independent-samples *t*-test revealed a statistically significant difference between the groups, $t(102) = 4.374$, $p < .001$. The experimental group obtained a higher mean posttest score (66.35) than the control group (46.21), with an observed mean difference of 20.14 points. These findings indicate that students participating in STEM-integrated POPBL demonstrated significantly higher posttest scientific literacy scores than students receiving conventional instruction. Nevertheless, the analysis was based on posttest comparisons and did not statistically adjust for baseline differences between the groups. Therefore, the findings establish a statistically significant difference in posttest performance but do not independently demonstrate that the instructional intervention caused the observed difference.

Table 6. Independent-Samples t-Test Results for Posttest Scientific Literacy Scores

Variable	Variance Assumption	Levene's *F*	Levene's *p*	*t*	*df*	*p* (Two-Tailed)
Scientific Literacy	Equal variances assumed	0.660	0.418	4.374	102	< .001
Scientific Literacy	Equal variances not assumed	—	—	4.374	99.849	< .001

Discussion

The findings indicate that students participating in STEM-integrated POPBL demonstrated more favorable scientific literacy outcomes than those receiving conventional science instruction. The experimental group's mean score increased by 14.19 points, whereas the control group's mean score decreased by 7.16 points, producing a descriptive difference in changes of 21.35 points. The statistically significant posttest difference further indicates that the experimental group achieved higher scientific literacy performance at the conclusion of the instructional period. These results are

consistent with the broader educational potential of interdisciplinary STEM instruction reported in previous investigations of science learning and cognitive performance (Anwar et al., 2022; De Loof et al., 2022; Le et al., 2023). However, the present findings should be distinguished from those studies because the instructional model, educational setting, assessment framework, and measured outcomes may differ. In particular, the present study focused on scientific literacy as a multidimensional competency rather than general academic achievement or broader cognitive performance. The observed differences therefore provide context-specific evidence concerning scientific literacy outcomes associated with STEM-integrated POPBL among Indonesian eighth-grade students. Nevertheless, the findings do not establish that the integration of STEM and POPBL independently produced the observed differences because the study did not isolate the separate contributions of these instructional components. Furthermore, the decline in the control group's posttest performance contributed substantially to the magnitude of the observed between-group difference. Consequently, the results should be interpreted as evidence of differing scientific literacy performance patterns across instructional conditions rather than definitive proof of the intervention's causal effectiveness.

The indicator-level findings provide additional insight into the scientific literacy competencies associated with the observed performance differences. The experimental group demonstrated its largest descriptive improvement in identifying scientific problems or phenomena, suggesting that this competency was particularly responsive within the instructional context examined. This pattern is theoretically compatible with the problem-orientation characteristics of POPBL, which position contextual scientific problems as the starting point for investigation and project development. Scientific modelling research has similarly emphasized the importance of engaging students in identifying, representing, and explaining scientific phenomena as part of meaningful scientific learning (Ke et al., 2021). Wiyarsi et al. (2021) also highlighted the educational relevance of socioscientific contexts for developing scientific thinking, although their instructional approach should not be regarded as equivalent to STEM-integrated POPBL. Unlike approaches primarily emphasizing the interpretation of socioscientific issues, the present intervention incorporated problem identification within a broader sequence of project-oriented learning activities. Nevertheless, the study did not independently assess the contribution of individual POPBL stages, making it inappropriate to attribute the observed improvement exclusively to problem orientation. The improvement in identifying scientific phenomena should therefore be interpreted as a descriptive outcome that is conceptually consistent with the instructional model rather than direct evidence of a specific pedagogical mechanism. This distinction is important because students' performance may also have been influenced by their prior knowledge, classroom interactions, and familiarity with the assessment tasks. Accordingly, the findings support further investigation into how problem-oriented instructional activities relate to specific dimensions of scientific literacy.

The improvement in applying scientific concepts in everyday life represents another important descriptive finding, with the experimental group's mean score increasing by 4.15 points. This pattern suggests that students demonstrated stronger posttest performance in connecting scientific knowledge with contextual situations following participation in STEM-integrated POPBL. Integrated STEM frameworks emphasize the importance of authentic problems and interdisciplinary applications, providing a conceptual basis for understanding why contextual knowledge application may be relevant to this instructional approach (Roehrig et al., 2021; Ortiz-Revilla et al., 2022). Similarly, previous studies have investigated project-based STEM learning in relation to science competencies and the application of scientific knowledge (Winarni & Purwandari, 2020; Saidaturrahmi et al., 2021). However, these investigations differ from the present study in their instructional arrangements and assessment objectives, limiting the extent to which their findings can be treated as directly comparable. The present results contribute to this discussion by documenting

changes in contextual scientific knowledge application within a STEM-integrated POPBL intervention. Nevertheless, the observed improvement cannot establish which particular STEM components were responsible for students' performance because the study did not separately measure the contributions of science, technology, engineering, and mathematics activities. The results also do not establish whether students transferred their knowledge to unfamiliar situations beyond those represented in the assessment instrument. Therefore, the improvement in contextual knowledge application should be interpreted as an encouraging assessment outcome rather than conclusive evidence of broad scientific knowledge transfer. Further research incorporating authentic performance assessments and delayed evaluations would be valuable for examining the extent and durability of students' contextual scientific understanding.

The indicators of interpreting data and drawing conclusions and understanding scientific concepts also demonstrated positive descriptive changes in the experimental group, although their improvements were smaller than those observed for problem identification and contextual application. The mean score for interpreting data and drawing conclusions increased by 2.77 points, while understanding scientific concepts improved by 2.71 points. These findings suggest that the experimental group's performance gains were distributed across all measured scientific literacy indicators rather than concentrated exclusively in one competency. Inquiry-oriented learning approaches have previously been investigated in relation to students' scientific reasoning, evidence interpretation, and scientific literacy development (Wen et al., 2020; Ke et al., 2021). Similarly, Koes-H and Putri (2021) examined PjBL-STEM in relation to scientific reasoning, while Hernawati et al. (2019) investigated project-based learning experiences and scientific literacy competencies. Although these studies provide relevant conceptual and empirical comparisons, their findings cannot establish that the same instructional mechanisms operated in the present investigation. In particular, the current study did not conduct inferential analyses for individual scientific literacy indicators, preventing conclusions about whether the differences in indicator-level changes were statistically significant. The smaller descriptive improvements in data interpretation and conceptual understanding may reflect differences in task demands, instructional emphasis, or students' initial competencies, but these explanations remain unverified. Consequently, the results highlight the importance of examining scientific literacy as a multidimensional construct while avoiding unsupported conclusions about the relative effectiveness of individual instructional activities. Future investigations could employ indicator-specific statistical analyses and classroom process data to examine how different learning activities are associated with particular scientific literacy competencies.

The substantial decline in the control group's scientific literacy performance requires particular attention when interpreting the comparative findings. Although the control group began with a slightly higher mean pretest score than the experimental group, its overall mean decreased from 53.37 to 46.21 following the instructional period. The decline was evident across all four scientific literacy indicators, with the largest reductions occurring in interpreting data and drawing conclusions and understanding scientific concepts. These patterns indicate that the observed posttest difference resulted from both improvement in the experimental group and reduced performance in the control group. However, the available data do not establish why the control group's scores declined, and explanations involving instructional quality, student motivation, assessment conditions, or classroom engagement cannot be confirmed without additional evidence. Differences in teacher practices, instructional exposure, school characteristics, or other contextual factors may also have influenced the observed outcomes. Because the study involved existing classroom groups from two schools, potential institutional and classroom-level differences represent important considerations when evaluating the findings. Furthermore, the independent-samples *t*-test did not account for potential dependence among students within the same classes or schools.

These methodological considerations limit the extent to which the observed posttest difference can be attributed specifically to STEM-integrated POPBL. Accordingly, the decline in control-group performance should be treated as an important empirical finding requiring further investigation rather than as evidence that conventional instruction necessarily reduces scientific literacy.

The present findings can also be interpreted in relation to previous investigations of POPBL and integrated STEM education. Examined integrated STEM education using POPBL in relation to twenty-first-century competencies, while Rizki and Suprapto (2024) investigated POPBL through an SR-STEM approach focusing on critical thinking in renewable energy learning. These studies provide relevant evidence concerning the applicability of project-oriented problem-solving approaches within STEM-related educational contexts. However, their emphasis on broader competencies differs from the present investigation, which specifically assessed scientific literacy through four indicators. Suwistika et al. (2024) also investigated POPBL in relation to scientific literacy, indicating that the relationship between POPBL and scientific literacy has already received empirical attention. Consequently, the contribution of the present study should not be framed as the first demonstration of POPBL's relevance to scientific literacy. Instead, its contribution lies in providing additional comparative evidence from Indonesian eighth-grade students participating in an instructional approach that explicitly integrates STEM with POPBL. The findings extend the discussion by documenting overall and indicator-level scientific literacy performance within a quasi-experimental pretest–posttest framework. Nevertheless, differences in research design, instructional implementation, participant characteristics, and assessment procedures should be considered before drawing conclusions about consistency across studies. This context-specific contribution is consistent with the need for more differentiated evaluations of integrated STEM approaches and their associated learning outcomes (Le et al., 2023).

Overall, the findings indicate that STEM-integrated POPBL was associated with higher posttest scientific literacy scores and positive descriptive changes across all four assessed competencies. The experimental group's improvement, together with the statistically significant posttest difference, provides preliminary evidence supporting the educational relevance of interdisciplinary, problem-oriented project-based instruction. Conceptually, the instructional approach offers opportunities to connect scientific problem identification, evidence interpretation, conceptual understanding, and contextual knowledge application through integrated learning activities. These characteristics are consistent with theoretical perspectives emphasizing authentic problems, interdisciplinary connections, and inquiry-oriented learning in STEM education (Roehrig et al., 2021; Ortiz-Revilla et al., 2022). However, the present study did not independently measure the contribution of each instructional stage or STEM component, preventing conclusions about the mechanisms responsible for the observed outcomes. The interpretation is further constrained by the nonequivalent group design, the absence of baseline-adjusted inferential analysis, and the lack of reported variability estimates and confidence intervals. Potential differences between schools and classrooms, together with the substantial decline in control-group performance, also complicate causal interpretation. In addition, the study assessed immediate post-intervention performance without a follow-up assessment, leaving the sustainability of the observed outcomes undetermined. Future research should incorporate baseline-adjusted statistical models, appropriate consideration of classroom clustering, detailed implementation evidence, and longitudinal assessments to strengthen conclusions regarding instructional effectiveness. Despite these limitations, the study contributes context-specific empirical evidence concerning scientific literacy outcomes associated with STEM-integrated POPBL and provides a basis for further investigation of interdisciplinary science instruction in Indonesian junior high schools.

Implications

The findings of this study provide theoretical and practical implications for integrating STEM-based Project-Oriented Problem-Based Learning (POPBL) into junior high school science education. Theoretically, the results contribute to existing research by demonstrating an association between STEM-integrated POPBL and scientific literacy outcomes across four competency indicators. Pedagogically, the findings suggest that teachers may incorporate contextual problems, collaborative projects, and interdisciplinary STEM activities to support students' scientific reasoning and knowledge application. The largest descriptive improvements in scientific problem identification and contextual knowledge application highlight the relevance of emphasizing these competencies in instructional planning. Meanwhile, the smaller improvements in data interpretation and conceptual understanding suggest the need for additional instructional support in these areas. At the curriculum level, STEM-integrated POPBL may inform the development of contextual and competency-oriented science learning materials. However, the nonequivalent group design and potential school-level differences limit causal interpretation and broader generalization. Future studies should employ more rigorous experimental designs, larger samples, and follow-up assessments to evaluate the effectiveness and sustainability of STEM-integrated POPBL in developing scientific literacy.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting its findings. The quasi-experimental nonequivalent control group design limits causal inference regarding the effectiveness of STEM-integrated Project-Oriented Problem-Based Learning (POPBL). Furthermore, the involvement of 104 eighth-grade students from two schools in Kupang restricts the generalizability of the results. Potential differences in students' initial abilities, instructional practices, and school environments may also have influenced the observed outcomes. The substantial decline in the control group's posttest scores requires further investigation to identify possible contributing factors. Additionally, the absence of baseline-adjusted analysis and follow-up assessments limits conclusions regarding instructional effectiveness and long-term learning retention. Future research should involve larger and more diverse samples using more rigorous experimental designs and appropriate statistical analyses. Incorporating classroom observations, student interviews, and longitudinal assessments is also recommended to clarify instructional mechanisms and evaluate the sustainability of scientific literacy development through STEM-integrated POPBL.

CONCLUSION

This study found that eighth-grade students participating in STEM-integrated Project-Oriented Problem-Based Learning (POPBL) achieved significantly higher posttest scientific literacy scores than those receiving conventional science instruction ($t(102) = 4.374$, $p < .001$). The experimental group's mean score increased from 52.16 to 66.35, representing a gain of 14.19 points, whereas the control group's mean score decreased from 53.37 to 46.21, indicating a decline of 7.16 points. The resulting posttest mean difference of 20.14 points demonstrates a substantial descriptive difference in performance between the two instructional conditions, although the decline in the control group contributed to this difference. At the indicator level, the experimental group demonstrated positive descriptive changes across all four scientific literacy competencies, with the largest improvements observed in identifying scientific problems or phenomena and applying scientific concepts in everyday situations. These findings extend existing research on STEM-integrated POPBL by providing context-specific comparative evidence concerning multidimensional scientific literacy outcomes among eighth-grade students in Kupang, Indonesia. From a practical perspective, the results suggest that science teachers may consider incorporating contextual

problem identification, interdisciplinary project activities, and evidence-based evaluation into instructional planning to provide opportunities for students to engage with scientific literacy competencies. Nevertheless, the nonequivalent group design, potential selection bias, school-level differences, and absence of baseline-adjusted analysis limit causal interpretation and generalizability beyond the participating students. Furthermore, the lack of follow-up assessment prevents conclusions regarding the long-term retention of scientific literacy competencies. Future studies should involve larger and more diverse samples, more rigorous experimental designs, longer instructional periods, and delayed posttests to examine the consistency and sustainability of the observed outcomes. Overall, STEM-integrated POPBL represents a promising instructional approach for further investigation in junior high school science education, although its effectiveness requires confirmation through more methodologically rigorous research.

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AUTHOR CONTRIBUTIONS STATEMENT

Arini Rahma Dhani contributed to the conceptualization, research design, methodology, data analysis, and manuscript preparation. M. Ulil Hac D contributed to the research methodology, data collection, and critical review of the manuscript. Familia Claudia Awil contributed to data collection, research implementation, and data organization. Christin Cisiliya Bentura contributed to instrument preparation, data collection, and manuscript review. Hendrikus Moan Liwu contributed to data interpretation, validation, and critical revision of the manuscript. All authors read and approved the final version of the manuscript.

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