

Project-Based Learning and Scientific Literacy in Primary Science: Quasi-Experimental Evidence from Grade 4 Students in North Sulawesi

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ABSTRACT

Objective: This study examined whether Project-Based Learning (PjBL) was associated with higher scientific-literacy achievement and greater learning gains among Grade 4 students studying pollination and seed dispersal. **Method:** A quasi-experimental nonrandomized control-group pretest-posttest design involved two intact classes in a public primary school in Tomohon, Indonesia (N = 40; 20 students per condition). Scientific literacy was assessed with a 20-item form selected from a 30-item pilot pool; the pilot pool showed Cronbach's alpha = .880. Analyses emphasized paired-samples t tests, Welch independent-samples t tests, mean differences, 95% confidence intervals (CIs), and Hedges' g. **Results:** Baseline performance was closely similar (M = 67.15 vs. 67.75; g approximately -0.08). The PjBL class increased to M = 85.35 (mean gain = 18.20), whereas the comparison class increased to M = 78.35 (mean gain = 10.60). At posttest, the PjBL class scored 7.00 points higher, Welch's $t(31.64) = 5.139$, $p < .001$, 95% CI [4.22, 9.78], $g = 1.59$, 95% CI [0.88, 2.31]. Gain scores differed by 7.60 points, Welch's $t(37.26) = 3.591$, $p = .001$, 95% CI [3.31, 11.89], $g = 1.11$, 95% CI [0.44, 1.78]. **Novelty:** The study provides effect-size-informed, context-specific evidence on Grade 4 scientific literacy while limiting inference to the two observed intact classes rather than claiming a broadly generalizable causal effect.

INTRODUCTION

Scientific literacy is a central goal of contemporary science education because children increasingly encounter scientific claims in classrooms, digital media, environmental issues, and everyday life. For primary-school learners, scientific literacy involves more than recalling scientific vocabulary; it requires observing phenomena, connecting evidence with explanations, interpreting simple representations, questioning claims, and communicating conclusions that are proportionate to the evidence available. These competencies are particularly relevant in Grade 4 science, where pollination and seed dispersal provide concrete opportunities to observe biological processes, interpret relationships between organisms and their environment, and explain how plants reproduce and disperse. Recent scholarship therefore treats scientific literacy as a functional capacity for making sense of the world rather than as accumulated content alone (Bossér, 2024; Busch & Rajwade, 2024; Rudolph, 2024). This emphasis is especially important in an age of misinformation (Andriani et al., 2025; Haviz et al., 2024; Osborne & Pimentel, 2023), while a recent systematic review of early scientific literacy highlights the value of learning experiences that connect concepts with purposeful activity, recognizable contexts, and sustained reasoning (Roy et al., 2025).

Primary school is a particularly important setting for this work because scientific understanding develops alongside language, reading, social participation, and children's emerging conceptions of how science itself works. Bartels and Lederman (2022) showed that elementary students' views of science and scientists require explicit pedagogical attention rather than being assumed to develop automatically. Ploj Vrtič (2022) likewise framed scientific literacy through the integration of scientific knowledge, inquiry processes, interpretation, and information use. At the same time,

Sun and Chan (2025) demonstrated that language and reading make distinct contributions to early science literacy. Children therefore need opportunities not only to receive scientific information but also to describe what they notice, compare possible explanations, interpret evidence, and justify ideas using developmentally appropriate language. Recent elementary project-based science research further suggests that cognitive flexibility—the capacity to consider and revise alternative solution pathways—is meaningfully connected with science and literacy achievement (Miller et al., 2025). Together, these findings support classroom environments in which scientific ideas become objects of inquiry, discussion, representation, and revision rather than isolated facts to be memorized.

Project-Based Learning (PjBL) is conceptually aligned with this ambition because it can organize learning around a meaningful problem or question that unfolds over time. High-quality PjBL typically involves explicit curriculum goals, sustained inquiry, collaboration, disciplinary practices, and an artifact or representation that makes students' thinking visible (Markula & Aksela, 2022). The educational value of the project does not lie in the attractiveness of the final product. It lies in the intellectual work needed to create it. When learners must observe a phenomenon, gather information, organize evidence, compare interpretations, revise a representation, or explain a conclusion to others, a project can become a structure for scientific reasoning. Meta-analytic evidence indicates that PjBL is generally associated with positive learning outcomes, although the magnitude of benefit varies according to duration, task structure, assessment, instructional support, and study quality (Zhang & Ma, 2023; Santhosh et al., 2023; Solichatin et al., 2022; Sukmawati et al., 2025; Sumo et al., 2024). Motivation in problem-, project-, and case-based environments is likewise shaped by the balance between challenge, autonomy, support, and perceived relevance (Wijnia et al., 2024). For elementary learners specifically, recent conceptual work has emphasized the need for manageable project phases, explicit scaffolding, and close alignment between project activity and intended competencies (Retno et al., 2025).

The contemporary evidence base therefore supports PjBL while cautioning against treating it as an instructional label that automatically guarantees superior learning. Farshad and Fortin (2026), in an umbrella review of PjBL meta-analyses, found generally positive effects on academic achievement, higher-order thinking, and twenty-first-century competencies, but also noted uneven methodological quality across the underlying syntheses. A systematic review of higher-order, critical, and critical-analytic thinking in problem- and project-based learning similarly showed that outcomes depend on the cognitive demands embedded in the learning environment rather than on the nominal presence of a project (Loyens et al., 2023). This distinction is particularly important in primary education, where the term project may refer to activities ranging from a loosely structured craft task to a sustained investigation requiring evidence, explanation, revision, and reflection. The more informative research question is therefore not simply whether PjBL works, but under what conditions, for which learners, and for which learning outcomes it appears to provide added value. Scientific literacy is a demanding outcome because it requires conceptual understanding to be coordinated with evidence use, interpretation, and communication.

Indonesian research provides a productive context for examining this relationship. Recent studies in science and primary education have shown that scientific literacy can be strengthened when instruction is connected with local knowledge, representational

supports, inquiry, and authentic contexts. Uslan et al. (2024) reported positive effects of a local-knowledge-based module on scientific literacy and thinking skills, while Fitria et al. (2023) showed that graphic-organizer-based learning can support the representational demands of elementary scientific-literacy learning. Astawan et al. (2025) further demonstrated that problem-based learning integrated with Balinese local wisdom was associated with reduced misconceptions and stronger scientific literacy. PjBL research in Indonesian primary education has frequently focused on learning outcomes, creativity, motivation, or critical thinking (Imron et al., 2025; Pangestu et al., 2024; Sari et al., 2025; Satria et al., 2025). Related elementary studies have also explored how project-oriented learning can be connected with learning beyond the classroom and with motivational structures (Januardi et al., 2025; Milah et al., 2025). These findings provide a strong rationale for active and contextual learning while leaving room for more focused evidence in which scientific literacy itself is the primary measured outcome.

Pollination and seed dispersal offer a particularly meaningful context for such an investigation. For Grade 4 learners, flowers, insects, fruits, seeds, wind, and animal movement are not distant scientific abstractions; they are phenomena that can often be observed in children's surroundings. This accessibility creates opportunities to move between observation and explanation. Learners can consider how floral structures relate to pollinating agents, why seeds differ in form, how organisms participate in reproduction, and how plant populations spread across environments. In pedagogical terms, the topic can support the connections scientific literacy requires: phenomenon to concept, observation to evidence, evidence to explanation, and explanation to communication. The topic is also sufficiently concrete to support age-appropriate inquiry without reducing learning to memorizing reproductive vocabulary. This contextual fit matters because PjBL is most likely to be educationally productive when the project question and the scientific phenomenon naturally require students to investigate, represent, and explain rather than when a project is added as an ornamental activity after content has already been transmitted.

Against this background, four connected gaps guided the study. First, a level-specific gap remains because scientific-literacy-focused PjBL evidence is less dense in the primary years than at later educational levels, even as recent reviews call for stronger early scientific-literacy research (Roy et al., 2025; Farshad & Fortin, 2026). Second, there is an outcome gap in the Indonesian literature because PjBL studies commonly emphasize achievement, creativity, motivation, or critical thinking rather than scientific literacy as the principal outcome. Third, there is a content-context gap: pollination and seed dispersal are accessible biological phenomena, yet they are not commonly used as the context for estimating PjBL-associated differences in Grade 4 scientific literacy. Fourth, there is a reporting gap. Statistical significance alone does not indicate whether a classroom difference is educationally trivial or substantial; mean differences, confidence intervals, gain patterns, and standardized effect sizes provide a more informative account of magnitude and uncertainty. The novelty of the study is therefore evidential rather than rhetorical. PjBL itself is not new, but the study combines a Grade 4 IPAS context, scientific literacy as the primary outcome, a biologically authentic topic, and effect-size-informed reporting within a transparent quasi-experimental comparison.

The present study examined whether the Grade 4 class receiving Project-Based Learning (PjBL) demonstrated stronger scientific-literacy outcomes than a comparison class receiving conventional instruction on the same science content. Because the instructional conditions were assigned to two pre-existing intact classes, with only one classroom representing each condition, the study was interpreted as a context-bound quasi-experimental comparison rather than as a broadly generalizable causal test. The directional expectation was that the PjBL class would show a higher posttest mean and a larger pretest-to-posttest gain. Based on this purpose, the study addressed three research questions: (RQ1) How did scientific-literacy scores change from pretest to posttest within the PjBL and comparison classes? (RQ2) To what extent did posttest scientific-literacy scores differ between the PjBL and comparison classes? (RQ3) To what extent did the two classes differ in learning gains and standardized effect magnitude?.

RESEARCH METHOD

Research Design and Inferential Target

The study employed a quantitative quasi-experimental, nonrandomized control-group pretest-posttest design using two pre-existing intact Grade 4 classes. Students remained in their regularly constituted classrooms and were not individually randomized or reassigned for research purposes. The research was conducted during the 2023/2024 academic year in a public primary school in Tomohon, North Sulawesi, Indonesia. The documented Grade 4 population comprised 40 students distributed across two parallel classes. Based on the original research records, Class IVB ($n = 20$) received the Project-Based Learning (PjBL) condition, whereas Class IVA ($n = 20$) received the comparison condition. The available records do not document a random allocation procedure at the classroom level; therefore, the instructional conditions were treated as nonrandom assignments of intact classes. Both classes studied the same IPAS content on pollination and seed dispersal and completed a pretest before instruction and a posttest after instruction. The use of intact classrooms preserved the natural instructional setting but imposed important inferential limitations. Because only one classroom represented each condition, treatment assignment was completely confounded with classroom membership and potentially with teacher, peer-composition, classroom-climate, and other unmeasured class-level characteristics. The design therefore supports an observed comparison between these two classes in this school rather than a cluster-level population treatment effect.

Instructional Conditions and Treatment Documentation

The research documentation identified Class IVB as receiving Project-Based Learning and Class IVA as receiving conventional instruction on the same science topic. This assignment was preserved as originally documented. However, the retained research records did not provide sufficiently detailed phase-level information to reconstruct the intervention protocol completely. The number and duration of meetings, exact driving question, project artifact, group composition, teacher actions at each phase, formative checkpoints, process rubric, and fidelity checklist were not retained in a form that allowed reliable reconstruction. Those elements were therefore not inferred retrospectively. In this article, PjBL refers to the instructional package identified and implemented in the original study. This limitation narrows construct-level interpretation: the study evaluates the classroom contrast associated with the reported

PjBL condition, but it cannot identify which PjBL component produced the observed difference or establish fidelity to every theoretically desirable feature of the model.

Participants and Data Collection

All 40 students represented in the two intact Grade 4 classes were included in the reported analyses, and no attrition was documented in the retained study report. Data collection used tests, observation, and documentation. The quantitative outcome analyzed in this article was the scientific-literacy test score because verifiable pretest and posttest descriptive and inferential statistics were available for this measure. Observation and documentation formed part of the original school-based research procedure but were not retained as systematically coded variables suitable for quantitative explanatory analysis. Pretests were administered before the instructional condition and posttests after instruction. Gain was defined as posttest minus pretest. The analysis reported here was based on the documented statistical output of the original study; individual-level raw scores were not available for the present reanalysis.

Scientific-Literacy Instrument

Scientific literacy was assessed using a topic-specific multiple-choice test addressing pollination and seed dispersal. Instrument development began with a 30-item pilot pool administered to 25 Grade 4 students. The retained item-analysis records indicated that 29 of the 30 pilot items met the validity criterion used in the original study. Twenty items were subsequently selected using the available evidence on item validity, item difficulty, and discrimination. Each item was scored dichotomously (1 = correct; 0 = incorrect or unanswered), and the raw score was converted to a 0-100 scale. The reliability output reported Cronbach's alpha = .880 for the original 30-item pilot pool. This coefficient is reported only as evidence of internal consistency for the pilot pool and is not attributed to the 20-item form because item selection can alter reliability. A separate reliability coefficient for the final administered 20-item assessment was not preserved in the available records.

The preserved instrument package also contains a 20-item operational blueprint designed to represent four scientific-literacy competencies: explaining scientific phenomena (5 items; 25%), interpreting data and evidence (6 items; 30%), evaluating or designing simple scientific inquiry (4 items; 20%), and applying science in context (5 items; 25%). Twelve items (60%) addressed pollination and eight (40%) addressed seed dispersal. Cognitive-demand mapping classified 4 items (20%) at C2, 9 (45%) at C3, and 7 (35%) at C4, so 80% of the operational item set targeted application, interpretation, or analytical reasoning at C3-C4 levels. Because the archival package labels this as an operational design and does not independently verify that every item was identical to the final administered form, these mappings are reported as evidence of intended competency coverage rather than as a fully verified item-by-item blueprint of the administered assessment. Accordingly, the outcome is interpreted conservatively as topic-specific scientific-literacy performance rather than as an exhaustive measure of global scientific literacy (Afnan et al., 2023; Himmah et al., 2024; Nasor et al., 2023; Sarini et al., 2024; Zhang et al., 2023).

Statistical Analysis

Analysis proceeded from description to within-class change and then to between-class comparison. Minimum, maximum, mean, and standard deviation summarized the four class-by-time score distributions. Shapiro-Wilk tests were used as the available

normality checks because each class contained 20 students. Within-class pretest-posttest changes were evaluated using paired-samples t tests. Between-class comparisons used independent-samples procedures, with Welch's t test emphasized when the equal-variance assumption was not supported. For the posttest comparison, the retained Levene output was $F = 4.327$, $p = .044$; the unequal-variance Welch result was therefore treated as the primary estimate. Two-sided statistical tests were evaluated at $\alpha = .05$, and software output displayed as .000 was reported as $p < .001$.

Effect Size, Gain Analysis, and Robustness of Interpretation

To reduce dependence on p values, the analysis reported mean differences, 95% confidence intervals, Cohen's d, and Hedges' g. Hedges' g was emphasized because its correction reduces small-sample bias in standardized mean differences. Baseline comparability was not inferred solely from a nonsignificant pretest test; the standardized pretest difference was also examined and was approximately $g = -0.08$, indicating a very small observed difference on the measured baseline outcome. Gain means and standard deviations were derived from the paired-samples output and compared using Welch's t test. The gain comparison functioned as a difference-in-change check that complemented the posttest contrast. Because individual raw data were not retained for the present reanalysis, ANCOVA adjusting posttest for pretest, residual diagnostics, student-level sensitivity analyses, and multilevel models could not be performed. The gain analysis was therefore interpreted as corroborative evidence based on documented summary statistics rather than as a substitute for a raw-data covariate-adjusted model.

Ethical and Transparency Requirements

The study involved primary-school students. Before submission, the corresponding author must insert the authentic institutional permission/ethics approval and consent-assent information from the original research records, consistent with the requirements applicable to the study. Institutional permission number: 1785/LPPM-UNIMA/Komite_Etik.11/2025.

Table 1. Quasi-experimental design and documented instructional conditions

Condition	Class / n	Pretest	Instruction	Posttest
PjBL	IVB / 20	O1	Project-Based Learning	O2
Comparison	IVA / 20	O1	Conventional instruction	O2

Note. O1 = pretest; O2 = posttest. The instructional condition was assigned at the intact-class level.

Table 2. Psychometric and competency evidence for the scientific-literacy assessment

Evidence	Documented value / status	Interpretive boundary
Pilot participants	25 Grade 4 students	Instrument-development sample
Initial item pool	30 multiple-choice items	Pollination and seed-dispersal context
Item validity	29 of 30 items met the original study criterion	Pilot-stage item-screening evidence
Main-study form	20 items	Selected using validity, difficulty, and discrimination information
Scoring	Correct = 1; incorrect/unanswered = 0; raw score / 20×100	Pretest and posttest reported on a 0-100 scale
Pilot internal consistency	Cronbach's $\alpha = .880$	Applies to the 30-item pilot pool
Final-form reliability	Not separately retained	$\alpha = .880$ is not attributed to the final 20-item form
Explaining scientific phenomena	5 items (25%)	Preserved operational blueprint

Evidence	Documented value / status	Interpretive boundary
Interpreting data and evidence	6 items (30%)	Preserved operational blueprint
Evaluating/designing simple inquiry	4 items (20%)	Preserved operational blueprint
Applying science in context	5 items (25%)	Preserved operational blueprint
Cognitive demand	C2 = 4 (20%); C3 = 9 (45%); C4 = 7 (35%)	80% of operational items at C3-C4
Content coverage	Pollination = 12 (60%); seed dispersal = 8 (40%)	Topic-specific coverage
Construct interpretation	Topic-specific scientific literacy	Not exhaustive measurement of all scientific-literacy dimensions

RESULTS AND DISCUSSION

Results

Table 3 summarizes the descriptive distributions and normality checks for scientific-literacy scores. The Shapiro-Wilk tests did not indicate statistically detectable departures from normality for any of the four class-by-time distributions (all $p > .05$). At baseline, the two classes had closely similar mean scores (PjBL: $M = 67.15$; comparison: $M = 67.75$), whereas the posttest means showed a clearer descriptive separation in favor of the PjBL class (85.35 vs. 78.35). The corresponding standard deviations and score ranges are reported in Table 3.

Table 3. Descriptive statistics and distributional checks for scientific-literacy scores

Group / Time	n	Min	Max	Mean	SD	Shapiro-Wilk p
PjBL - Pretest	20	55	80	67.15	7.541	.363
PjBL - Posttest	20	80	90	85.35	3.200	.200
Comparison - Pretest	20	55	80	67.75	6.904	.790
Comparison - Posttest	20	70	88	78.35	5.184	.534

Within-class changes are summarized in Table 4. Both classes showed statistically detectable improvement from pretest to posttest. However, the magnitude of change was descriptively greater in the PjBL class, which gained 18.20 points on average, compared with a 10.60-point gain in the comparison class. The complete paired-samples t-test estimates and confidence intervals are provided in Table 4.

Table 4. Within-class pretest-posttest changes in scientific literacy

Group	Mean Gain	SD Gain	t	df	p	95% CI for Pre-Post Difference
PjBL	18.20	7.150	-11.384	19	< .001	[-21.546, -14.854]
Comparison	10.60	6.202	-7.644	19	< .001	[-13.503, -7.697]

Note. Positive mean gain is defined as posttest minus pretest, whereas the reported confidence intervals correspond to the paired-samples output expressed as pretest minus posttest.

The primary between-class comparisons are presented in Table 5. The pretest difference was negligible in standardized terms (Hedges' $g = -0.08$), supporting the descriptive observation that the two classes began with closely similar measured baseline performance. At posttest, the PjBL class scored 7.00 points higher than the comparison class, with Hedges' $g = 1.59$. The gain-score comparison showed the same directional pattern: the PjBL class improved by 7.60 points more than the comparison class, corresponding to Hedges' $g = 1.11$. The confidence intervals for both posttest and gain differences excluded zero; full Welch-test statistics and confidence intervals are reported in Table 5.

Taken together, Tables 3-5 show a coherent pattern: the two classes began with closely similar observed pretest performance, both improved during the instructional period, and the class receiving PjBL showed the higher posttest score and the larger gain. These statistics describe a strong observed classroom contrast, but because only one intact class represented each instructional condition, they do not constitute independent replication of a treatment effect across multiple classes.

Table 5. Between-class comparisons and standardized effect sizes

Outcome	Mean Difference	Welch t (df)	p	95% CI	Hedges' g
Pretest	-0.60	-0.262 (37.71)	.794	[-5.23, 4.03]	-0.08
Posttest	7.00	5.139 (31.64)	< .001	[4.224, 9.776]	1.59
Gain	7.60	3.591 (37.26)	.001	[3.313, 11.887]	1.11

Note. Positive posttest and gain differences indicate higher values in the PjBL class. Hedges' g is emphasized because of its small-sample bias correction.

Discussion

The principal finding was that students in the class receiving PjBL-labelled instruction achieved higher topic-specific scientific-literacy scores at posttest and showed a larger pretest-posttest gain than students in the comparison class. The posttest difference corresponded to Hedges' $g = 1.59$ and the gain difference to $g = 1.11$, both large standardized contrasts in the observed sample. This direction is consistent with meta-analytic research showing that PjBL can support learning when projects are cognitively purposeful and sufficiently structured (Zhang & Ma, 2023; Santhosh et al., 2023). It is also compatible with Farshad and Fortin's (2026) umbrella review, which found generally positive PjBL effects while emphasizing variability in design quality and evidence strength. The present study therefore adds a focused primary-school data point to a literature that is broadly encouraging but methodologically heterogeneous.

The baseline pattern strengthens the descriptive interpretation without resolving the limitations of nonrandom assignment. Pretest means differed by only 0.60 points and the standardized difference was approximately $g = -0.08$, making it less plausible that a large initial difference on the measured outcome alone explains the posttest contrast. Baseline similarity, however, does not establish equivalence on unmeasured characteristics. Because one intact classroom represented each instructional condition, the PjBL condition was inseparable from classroom membership. Differences in teacher instructional style, classroom climate, peer composition, participation patterns, prior classroom routines, attendance, home learning support, language resources, access to learning materials, time on task, or the amount and quality of instructional support could therefore have contributed to the observed posttest difference. These variables were not systematically measured in the retained data and cannot be statistically isolated from the instructional condition. The higher posttest performance should consequently be interpreted as an observed contrast between two classroom contexts associated with different instructional conditions, not as evidence that the difference was attributable exclusively to PjBL.

The result is theoretically plausible because PjBL can coordinate several learning opportunities that scientific literacy requires. Scientific literacy asks learners to move among phenomena, concepts, evidence, interpretation, and communication. A phenomenon-centered project can create reasons for children to make those moves: students may need to observe, compare, gather information, represent relationships, discuss alternatives, revise ideas, and communicate an evidence-based product.

Markula and Aksela (2022) describe such features as central to robust science PjBL, while Miller et al. (2025) show that project-based elementary science environments can support cognitive flexibility together with science and literacy achievement. Retno et al. (2025) similarly emphasize deliberate design and scaffolding in elementary PjBL (Septiadevana & Abdullah, 2024). These studies help explain why project work may be productive when the project becomes a vehicle for thinking rather than merely a vehicle for making.

Pollination and seed dispersal are particularly suitable for this form of learning because the phenomena are close to children's everyday ecological experience. Flowers, insects, fruits, seeds, wind, and animal movement provide concrete entry points into ideas that might otherwise remain abstract. Familiar phenomena can reduce the distance between the child and the reasoning task, but familiarity alone is not sufficient. The educational value emerges when observation is transformed into evidence and evidence is transformed into explanation. This process aligns with contemporary functional conceptions of scientific literacy that emphasize the use of scientific understanding in recognizable situations rather than the possession of isolated facts (Bossér, 2024; Busch, 2024). It also resonates with Roy et al.'s (2025) systematic review, which highlighted the value of early scientific-literacy experiences connected with real contexts and purposeful activity.

The comparison-class improvement is pedagogically important. Its mean gain of 10.60 points was statistically detectable and should not be interpreted as instructional failure. Both classes learned; the difference concerns the magnitude of learning observed under the two conditions. This framing is educationally more realistic than positioning conventional instruction as a non-learning condition. Teachers routinely choose among approaches that may all generate progress but differ in authenticity, cognitive demand, collaboration, representation, feedback, and use of evidence. The observed 7.60-point difference in gain is consistent with an added-value pattern for the PjBL class in this sample. It does not imply that direct explanation, guided practice, or other conventional techniques have no place in primary science. Indeed, strong project learning often depends on timely teacher explanation and scaffolding within the broader inquiry sequence.

Indonesian evidence reinforces the importance of contextual and representational support. Usulan et al. (2024) found that local-knowledge-based modules improved scientific literacy and thinking skills, while Fitria et al. (2023) demonstrated the usefulness of graphic organizers for structuring elementary scientific-literacy learning. Astawan et al. (2025) showed that locally integrated problem-based learning can reduce misconceptions while strengthening scientific literacy (Lestari et al., 2022; Pujawan et al., 2022). PjBL studies have likewise documented gains in conceptual understanding, creativity, critical thinking, and broader learning outcomes when projects are connected with STEM or carefully designed instructional supports (Prajoko et al., 2023; Pangestu et al., 2024; Satria et al., 2025). Within elementary education, Januardi et al. (2025) and Milah et al. (2025) further illustrate the adaptability of project-oriented learning across learning environments and literacy outcomes. Taken together, this work suggests that the educational power of PjBL lies less in the word project than in the quality of the intellectual and social work organized around it.

Measurement quality remains an important boundary on the interpretation of the large observed effects. The retained reliability coefficient of .880 applies to the 30-item pilot pool rather than explicitly to the final 20-item form, and a complete competency blueprint for the final instrument was not retained. Scientific literacy is multidimensional, so a single total score should not be assumed to represent every domain of the construct. Recent instrument-development work emphasizes the importance of mapping knowledge, competencies, and contexts explicitly when scientific literacy is assessed (Zhang et al., 2023). For this reason, the present outcome is best described as topic-specific scientific-literacy performance. This narrower interpretation does not erase the between-class difference; instead, it prevents the instrument from supporting claims that exceed the evidence available for its construct coverage.

A large average contrast also does not mean that every child experienced the project in the same way. Younger learners differ in language resources, prior knowledge, confidence, motivation, and comfort with collaboration. Sun and Chan (2025) show that language and reading contribute to early science literacy through different pathways, while Wijnia et al. (2024) demonstrate that motivation in project-oriented learning is shaped by design characteristics and support. In practice, project work can become cognitively unequal if a small number of confident students dominate decision-making while others contribute mainly to decoration or presentation. Primary-school PjBL therefore needs structures that keep each child intellectually present: rotating roles, individual observation notes, vocabulary support, short written explanations, graphical organizers, teacher checkpoints, and moments of individual reflection. Humanizing project learning means using collaboration to widen participation rather than allowing group work to hide unequal cognitive engagement.

This tension is especially important for primary-school learners because PjBL combines learner agency with substantial demands for planning, information selection, collaboration, progress monitoring, product construction, and scientific explanation. This can create an autonomy paradox: the freedom intended to strengthen agency may become cognitively counterproductive when young learners do not yet possess sufficient domain knowledge, self-regulatory routines, or task-management strategies to use that freedom effectively. From the perspective of Cognitive Load Theory, novel and poorly structured demands can consume limited working-memory resources that are also needed for conceptual reasoning (Sweller et al., 2019). Evidence with elementary learners shows that metacognitive scaffolding within PjBL can support learning and higher-order performance (Wang et al., 2024), while Grade 4 science research indicates that structured scaffolds such as worked examples can reduce extraneous cognitive load and especially support learners with lower prior knowledge (Xu et al., 2026). Primary-school PjBL may therefore be most productive when autonomy is structured rather than unrestricted: teachers can constrain choices, segment complex tasks, model scientific reasoning, provide phase-specific prompts and collaborative roles, and gradually fade support as students become more capable of regulating the project independently. The present study did not directly measure autonomy, cognitive load, or phase-specific scaffolding, so these mechanisms are offered as theoretically plausible interpretations rather than empirically tested mediators of the observed classroom difference.

The findings also carry implications for school-level instructional management. PjBL should be treated as an instructional system rather than an occasional classroom event. Teachers need time to design questions that are genuinely linked to curriculum goals, anticipate misconceptions, choose accessible materials, and construct rubrics that value evidence and reasoning as much as product quality. School leaders can support this work through collaborative planning, shared resource banks, moderation of project rubrics, and professional discussion about evidence of individual learning. Technology can be useful, but it should be selected for pedagogical function rather than symbolic innovation. Digital libraries, augmented-reality environments, and differentiated interactive tools have shown promise in recent Indonesian science education (Prastiti & Adi, 2024; Herowati & Andaryani, 2026; Wilujeng et al., 2025), yet low-cost local plants, observation journals, diagrams, tables, and handmade models can serve similar epistemic functions when they help children collect, organize, interpret, and communicate evidence.

The contribution of the study is consequently best understood at three levels. Empirically, it adds a quasi-experimental comparison involving Grade 4 students, an age group for which scientific-literacy-focused PjBL evidence remains comparatively limited. Substantively, it centers scientific literacy rather than general achievement alone and uses an IPAS topic connected with children's everyday environment. Analytically, it complements significance testing with baseline standardized difference, confidence intervals, gain comparison, and Hedges' g , making the magnitude and uncertainty of the classroom contrast more visible. None of these procedures is novel by itself. The contribution lies in combining them within a clearly bounded primary-school context, making inferential limits explicit, and highlighting a design problem of particular importance for younger learners: productive PjBL requires a deliberate balance between learner autonomy, scaffolding, and cognitive demand rather than assuming that more autonomy automatically produces better learning.

CONCLUSION

Fundamental Finding: The study found that the Grade 4 class receiving PjBL-labelled instruction showed a stronger observed learning trajectory in topic-specific scientific literacy than the comparison class. Both classes improved, but the PjBL class achieved the higher posttest mean and the larger gain. The between-class posttest difference was 7.00 points (Hedges' $g = 1.59$), while the gain difference was 7.60 points ($g = 1.11$). Within this school context, the pattern was consistent with the proposition that project-oriented learning can provide additional opportunities for students to connect observable phenomena, scientific concepts, evidence, representations, and explanations. **Implication:** The practical implication is not that every science lesson should become a project or that conventional instruction is ineffective. Rather, PjBL appears most defensible when the project is deliberately aligned with scientific-literacy goals, when autonomy is structured with developmentally appropriate scaffolding, when each learner remains cognitively engaged, and when assessment values reasoning and evidence rather than product aesthetics. **Limitation:** The findings should be interpreted within important limits. Only one intact class represented each instructional condition, so treatment could not be separated from class- or teacher-level influences; the sample was small and drawn from one school; detailed intervention-fidelity records were unavailable; reliability of the final 20-item form was not retained; the operational

competency blueprint could not be independently verified against every item in the final administered form; and individual raw data were unavailable for baseline-adjusted or multilevel analysis. **Future Research:** Future studies should replicate the design across multiple schools and classrooms, consider class-level randomization where feasible, document PjBL fidelity prospectively, retain student-level data, report reliability for the final administered instrument, use verified competency blueprints, measure cognitive load and learner autonomy directly, and include delayed or authentic performance assessments to examine retention and transfer.

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