

Research paper

Learning For Strengthening Scientific Literacy of Pre-Service Teachers in Elementary Education Programs

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ABSTRACT

Strengthening scientific literacy among pre-service elementary teachers requires learning experiences that connect scientific reasoning, reflection, problem solving, and communication with pedagogical meaning. This study aimed to develop, implement, and evaluate the EXARIS-PBL framework across different institutional contexts. A sequential exploratory mixed methods design was employed involving pre-service elementary teachers from three Indonesian universities. The research consisted of qualitative exploration, framework development, multi-institution implementation, quantitative assessment, and qualitative investigation of learning processes. Quantitative findings showed that EXARIS-PBL implementation was associated with positive changes in students' scientific literacy achievement, although the magnitude and statistical evidence varied across institutional contexts. The strongest effectiveness evidence was identified at UNNES, while the UPI implementation showed no significant adjusted posttest difference between groups. The UNP development evaluation demonstrated descriptive improvement following model implementation. Qualitative findings revealed three interconnected developments: progressive pedagogical awareness, professional teacher identity formation, and evidence-based collaboration and scientific communication. Integration of quantitative and qualitative evidence indicated that EXARIS-PBL supports scientific literacy development through structured processes of problem exploration, evidence analysis, reflection, conceptual and pedagogical integration, collaboration, and communication. The findings suggest that EXARIS-PBL provides a context-responsive framework for supporting scientific literacy development and professional preparation of future elementary teachers, while emphasizing the importance of institutional conditions and implementation contexts.

Keywords: teacher education, scientific literacy, pre-service elementary teachers, problem-based learning, EXARIS-PBL

Scientific literacy is increasingly important for enabling individuals to understand scientific phenomena, evaluate evidence, construct reasoned explanations, and make informed judgments about science-related issues. Contemporary science education therefore extends beyond the acquisition of factual knowledge toward the ability

to use scientific understanding in meaningful contexts. Bossér (2024) emphasizes that functional scientific literacy requires learners to reason, communicate, and apply scientific knowledge, while Torrijos-Torrijos-Muelas et al. (2023) highlight the importance of strengthening scientific competencies among teachers and pre-service teachers. For teacher education, this demand is particularly significant because scientific understanding must ultimately be transformed into learning experiences that enable future pupils to engage with science in thoughtful and evidence-informed ways.

Pre-service elementary teachers occupy a distinctive position in this process because they will shape children's early encounters with science. Their preparation requires more than conceptual knowledge; they need opportunities to investigate phenomena, interpret evidence, construct explanations, and consider how scientific ideas can be communicated pedagogically. Seung et al. (2023) showed that engagement with scientific practices can support elementary pre-service teachers' understanding of science learning, while Fan (2024) reported that inquiry-oriented instruction can strengthen scientific competence and interdisciplinary knowledge. Uskola & Puig (2023) further demonstrated the value of contextual scientific problems for developing prospective teachers' capacity to reason about complex issues.

This dual demand distinguishes scientific literacy in teacher education from scientific competence developed solely for individual academic purposes. Prospective elementary teachers need to reason scientifically while simultaneously learning to anticipate how scientific ideas may be represented, questioned, or misunderstood by children. Scientific literacy in this context therefore connects disciplinary understanding with pedagogical reasoning. Teacher preparation consequently requires learning experiences in which prospective teachers encounter scientific problems as learners while also developing the capacity to transform those experiences into meaningful future classroom practices.

Recent evidence indicates that this need remains unresolved in teacher preparation. Pre-service teachers often conceptualize scientific literacy primarily in terms of content and procedural knowledge and the practical utility of science, while broader societal and epistemic dimensions receive less attention (Kinyota & Kajungu, 2024). Pre-service elementary teachers may also recognize relevant scientific issues without sufficiently translating them into explicit curricular connections and teaching strategies (Saribas, 2025), while incomplete understandings of how scientific knowledge is constructed and interpreted have also been reported in early-years teacher education (Ampatzidis & Ergazaki, 2026). These limitations are particularly consequential for elementary teacher preparation because future teachers are expected not only to reason scientifically themselves but also to transform scientific understanding into meaningful learning experiences for children. Strengthening scientific literacy during initial teacher education therefore represents an important professional preparation need that requires learning experiences connecting scientific reasoning with pedagogical decision making.

Learner-centered approaches have received considerable attention as means of supporting these competencies. Inquiry-based science education provides opportunities to formulate questions, examine evidence, and construct explanations. However, Strat et al. (2024) found that learning science through inquiry and learning how to teach through inquiry are not always sufficiently connected in teacher education. Scientific communication and argumentation also represent important dimensions of scientific literacy because learners need to justify claims and communicate evidence-based explanations. Structured argumentation has been shown to support pre-service teachers' reasoning and communication competencies (Altun & Ozsevec, 2025; Şahin Kalyon & Özdem Yılmaz, 2025), although prospective teachers require explicit support before they can effectively facilitate such discourse in their own classrooms (Wess et al., 2023).

Among learner-centered approaches, Problem-Based Learning (PBL) provides a particularly relevant foundation because it organizes learning around meaningful problems that require investigation, reasoning, collaboration, and knowledge construction. Recent evidence indicates that problem-centered learning can facilitate higher-order and critical thinking when learners actively engage with complex problems (Loyens et al., 2023). Wijnia et al. (2024) further reported positive motivational effects across problem-, project-, and case-based learning environments. More recent meta-analytic evidence confirms the potential of PBL to support higher-education learning outcomes while showing that its effects depend on instructional, methodological, and contextual characteristics (Erdem et al., 2026). These findings indicate that PBL offers a strong foundation for active learning, although the quality of its outcomes depends substantially on how the learning process is organized.

This issue is especially relevant in teacher education. Prospective teachers need to experience problem-centered learning as learners before considering how comparable learning experiences can be facilitated in future classrooms. Magaji et al. (2024) found that PBL remains insufficiently utilized in pre-service science teacher education and emphasized the need to connect direct experience with future pedagogical use. Akcay & Benek (2024) similarly showed that the effectiveness of PBL in science education depends on instructional design and facilitation rather than exposure to problems alone. Context-based interventions further indicate that scientific literacy develops more meaningfully when learners are guided to relate scientific problems to evidence, reasoning, and relevant social contexts (Çalık & Wiyarsi, 2025).

These findings point to an unresolved pedagogical problem. Engaging learners with a scientific problem does not necessarily ensure that they systematically evaluate evidence, reconsider their reasoning, connect scientific knowledge with pedagogical considerations, and communicate defensible explanations. Kinskey & Zeidler (2024) showed that pre-service elementary teachers can experience difficulty when translating socioscientific reasoning into pedagogical decisions. Mesci et al. (2023) likewise highlighted the importance of explicit and reflective instruction in helping prospective science teachers reconsider how scientific knowledge is constructed and used. More recent work suggests that scientific literacy can be strengthened when reasoning and evidence-based communication are deliberately embedded within the learning process rather than treated as peripheral activities (Mesci et al., 2025).

The unresolved gap, therefore, concerns how problem exploration, evidence analysis, structured reflection, conceptual-pedagogical connections, and scientific communication can be organized as an interconnected learning sequence for strengthening the scientific literacy of pre-service elementary teachers. Previous inquiry, argumentation, and PBL studies provide substantial evidence for these individual processes, yet they are often examined as separate instructional components. Problem solving does not necessarily require learners to evaluate how their reasoning develops; inquiry does not automatically bridge scientific understanding with pedagogical decision making; and reaching a solution does not guarantee that learners can communicate evidence-based explanations. This gap is particularly important in elementary teacher education because scientific literacy must function both as a competence that future teachers themselves develop and as a foundation for the science learning they will later facilitate.

To address this gap, the present study proposes EXARIS-PBL, which integrates Problem-Based Learning with five interconnected learning stages: Explorer, Analysis, Reflection, Integration, and Share. Explorer engages learners with contextual scientific phenomena and problem formulation; Analysis focuses on examining information, evidence, and possible explanations; Reflection encourages learners to evaluate their understanding and reasoning processes; Integration links scientific concepts with contextual and pedagogical applications; and Share provides opportunities to communicate and negotiate evidence-based explanations. Rather than positioning problem resolution as the endpoint of learning, the sequence extends learning toward reflection, conceptual connection, pedagogical meaning-making, and scientific communication. In this way, EXARIS-PBL maintains the problem-centered character of PBL while providing a clearer progression through which scientific reasoning can develop into professionally relevant understanding.

The contribution of EXARIS-PBL lies in its explicit organization of problem exploration, evidence analysis, structured reflection, conceptual-pedagogical connection, and scientific communication within a coherent learning architecture. Reflection is embedded in the reasoning process so that learners reconsider how evidence and explanations are constructed. The Integration stage then bridges scientific understanding with contextual and pedagogical applications, while Share requires learners to articulate and negotiate evidence-based explanations. This structure is particularly relevant for pre-service elementary teachers because it links scientific literacy with the pedagogical reasoning expected in their future profession. In addition, implementation across different institutional settings provides methodological merit by examining how the same learning framework operates under authentic and contextually varied teacher education conditions.

Accordingly, this study aims to develop, implement, and evaluate the EXARIS-PBL framework for strengthening scientific literacy among pre-service elementary teachers across different institutional contexts. Specifically, this study addresses three objectives: (1) to develop and evaluate the EXARIS-PBL framework for pre-service elementary teacher education; (2) to examine scientific literacy outcomes associated with EXARIS-PBL implementation across institutional contexts; and (3) to investigate the learning processes underlying EXARIS-PBL implementation through the integration of quantitative and qualitative evidence.

LITERATURE REVIEW

The theoretical foundation of this study is organized around four interconnected areas: scientific literacy as a professional competence in elementary teacher education, problem-centered learning in pre-service teacher preparation, the role of reflection and evidence-based reasoning in professional learning, and the conceptual development of the EXARIS framework. Rather than treating these areas as independent perspectives, this review examines how they converge to support a learning framework in which pre-service elementary teachers engage with scientific problems, evaluate evidence, reflect on their reasoning, connect scientific understanding with pedagogical contexts, and communicate their ideas.

Scientific literacy as a professional competence in elementary teacher education

Scientific literacy in teacher education involves more than possessing scientific content knowledge. Future teachers must be able to interpret scientific information, evaluate evidence, understand how scientific knowledge

is constructed, and use such understanding when making instructional decisions. Recent evidence suggests that pre-service teachers do not always conceptualize scientific literacy in this broad sense. Kinyota & Kajungu (2024), for example, found that pre-service teachers' perspectives tended to emphasize content and procedural knowledge as well as the practical utility of science, while broader societal dimensions of scientific literacy received less attention. This indicates that developing scientific literacy in teacher preparation requires deliberate experiences that extend prospective teachers beyond content mastery.

The conceptual understanding of scientific literacy among pre-service teachers is also multidimensional rather than uniform. Mi et al. (2025) identified several distinct ways in which pre-service physics teachers conceptualized scientific literacy, including scientific content, the nature of science, the relationship between science and society, and judgments about the reliability of information. Similarly, Ates et al. (2025) reported that pre-service science teachers frequently described the purposes of science education in terms of factual knowledge and everyday usefulness, whereas engagement with science in societal contexts was less evident. These findings suggest that teacher education needs to help prospective teachers connect what science is, how scientific knowledge is evaluated, and why scientific reasoning matters beyond the immediate academic setting.

For pre-service elementary teachers, this issue is particularly consequential because their own experiences with scientific practices may shape the type of science learning they later facilitate. Bennion & Davis (2024) showed that pre-service elementary teachers entered science learning with varied prior experiences that influenced how they engaged in scientific practices. Developing competence in such practices therefore requires opportunities to participate actively in scientific sense-making rather than simply learn about scientific methods conceptually.

Recent research also indicates a gap between understanding a scientific issue and transforming that understanding into pedagogically meaningful learning. Saribas (2025) found that many pre-service elementary teachers could identify relevant environmental and sustainability issues, yet their reflections often lacked sufficiently explicit curricular connections and teaching strategies. Related evidence from early-years teacher education indicates that pre-service teachers may also hold incomplete understandings of the nature of science, particularly regarding how scientific knowledge is constructed and interpreted (Ampatzidis & Ergazaki, 2026). Collectively, these studies position scientific literacy in elementary teacher education as a professional competence that requires scientific understanding to be linked with reasoning, contextual application, and pedagogical interpretation.

Problem-centered learning in pre-service teacher education

Problem-centered learning provides an important pedagogical basis for developing these competencies because it places learners in situations where knowledge must be constructed and applied in response to meaningful problems. Within teacher education, the value of such learning extends beyond solving the immediate problem. Student teachers can also reconsider their assumptions about learning and teaching as they participate in problem-solving processes. Han (2026) demonstrated that engagement in Problem-Based Learning (PBL) contributed to changes in student teachers' professional identities and pedagogical meanings, suggesting that PBL can function as both a learning strategy and a professional learning experience.

Evidence from elementary teacher education also supports the potential of problem- and project-oriented learning for scientific literacy. Badaruddin et al. (2024) found that a project-based learning design integrated with STEM and supported by a science encyclopedia produced positive improvements in scientific literacy among pre-service elementary teachers. Although project-based and problem-based learning are conceptually distinct, this evidence is relevant because both approaches place authentic or meaningful problems at the center of active knowledge construction. Importantly, the study also suggests that the effectiveness of problem-oriented learning may depend on the instructional resources and structures surrounding the learning process rather than on the presence of a problem alone.

A similar pattern can be observed in inquiry-oriented teacher preparation. Delgado-Iglesias et al. (2024) found that pre-service primary teachers' competence in conducting inquiry improved after direct instructional experience, although participants continued to require preparation in the didactic dimensions of implementing inquiry. This distinction is important: knowing how to conduct an investigation does not automatically translate into knowing how to transform investigation into effective teaching.

Structured support is also relevant to scientific reasoning itself. Gizaw et al. (2025) reported that explicit science process skills instruction supported the development of several dimensions of scientific reasoning among pre-service science teachers, particularly the control of variables and hypothetical-deductive reasoning. At the same time, improvement was not uniform across all reasoning dimensions. Such findings indicate that scientific reasoning should not be treated as an automatic consequence of participation in active learning; it benefits from deliberately sequenced instructional support.

Reflection, evidence-based reasoning, and pedagogical meaning-making

Reflection provides an important mechanism for transforming learning experiences into more explicit forms of scientific and pedagogical reasoning. In teacher education, reflection enables learners to revisit the assumptions, evidence, and decisions underlying their understanding rather than merely evaluate whether a task has been completed successfully. Prayogi et al. (2025) demonstrated that embedding structured reflective processes within scientific inquiry substantially strengthened critical thinking among pre-service science teachers. Their findings support the view that inquiry becomes more cognitively productive when learners are explicitly encouraged to monitor, evaluate, and reconsider their reasoning.

Reflection also contributes to the transformation of disciplinary experience into pedagogical knowledge. Li et al. (2024) found that repeated reflection and dialogic feedback helped pre-service teachers develop more situated and dynamic pedagogical content knowledge. Importantly, reflection was not treated simply as an individual retrospective exercise. Through dialogue and feedback, prospective teachers articulated their reasoning, reconsidered instructional decisions, and connected teaching experiences with student understanding. This provides a relevant theoretical basis for positioning reflection as a bridge between scientific understanding and pedagogical meaning-making.

Evidence from elementary science teacher preparation reinforces this connection. Arias et al. (2024) examined pre-service elementary teachers' reflections on rehearsals and classroom enactments across three universities. Rehearsal-based reflection supported attention to student sense-making and encouraged the use of evidence and reasoning when interpreting teaching events. However, patterns differed when prospective teachers moved into more complex classroom settings. This suggests that reflective competence is situated and needs repeated opportunities for enactment across contexts rather than being acquired through a single reflective activity.

The transfer of scientific understanding across contexts presents a related challenge. Şen & Öztuna Kaplan (2025) found that pre-service science teachers generally demonstrated limited understanding of the nature of science and only limited transfer of this understanding to socioscientific reasoning. The finding is significant for scientific literacy because possessing scientific knowledge or epistemic concepts does not guarantee their application when learners confront contextual problems. A learning model intended to strengthen scientific literacy therefore needs to make the movement from scientific understanding to contextual reasoning explicit.

The EXARIS framework and its extension through problem-based learning

The EXARIS model provides a recent instructional architecture for organizing scientific learning around a progressive sequence of exploration, analysis, reflection, integration, and communication. Januar et al. (2025) originally developed EXARIS for elementary science education through an instructional development process involving expert validation, implementation, and field evaluation. The original model consists of Exploration, Analysis, Reflection, Integration, and Sharing, with each component representing a transition from engagement with a phenomenon toward increasingly analytical, reflective, connected, and communicative learning.

The original EXARIS study demonstrated the feasibility of organizing scientific learning through this sequence and reported improvements in scientific and digital literacy among elementary students (Januar et al., 2025). Of particular relevance to the present study are the Reflection and Integration components, which make the reconsideration and synthesis of understanding explicit, and the Sharing component, which treats scientific communication as part of learning rather than as an activity that occurs only after learning has been completed.

Nevertheless, the initial EXARIS model was developed and evaluated with elementary-school learners. Its application does not directly address the additional professional demands faced by pre-service elementary teachers, who need to develop scientific understanding while simultaneously learning to interpret that understanding pedagogically. Contemporary evidence reviewed above shows that prospective teachers can experience difficulty connecting scientific concepts with societal contexts, transferring epistemic understanding across situations, and converting inquiry experiences into pedagogical decisions. These demands justify extending the EXARIS architecture into a teacher-education context.

The present study therefore positions PBL as the problem-centered structure within which the EXARIS sequence operates. PBL supplies contextual problems that initiate investigation and collaborative reasoning, while the EXARIS stages provide a progression for what learners do with the experience: Explorer initiates engagement with a contextual scientific problem; Analysis directs attention toward information and evidence; Reflection makes evaluation of reasoning explicit; **Integration** connects scientific understanding with contextual and pedagogical meaning; and Share provides space for communicating and negotiating evidence-based explanations. The resulting EXARIS-PBL framework is consequently conceptualized not as the simple addition of two models, but as an instructional organization in which problem-based activity is extended through explicit reflective, connective, and communicative processes.

State of the art and positioning of the present study

Recent research reveals several advances relevant to the development of EXARIS-PBL. Studies have examined how pre-service teachers conceptualize scientific literacy, how they engage in scientific practices, how inquiry competence develops, how problem- and project-centered experiences influence learning, and how reflection supports professional reasoning. At the same time, these strands remain only partially connected.

First, studies of scientific literacy among pre-service teachers identify limitations in how prospective teachers conceptualize and apply scientific knowledge, but most are diagnostic rather than intervention-based. Second, problem-, project-, and inquiry-oriented interventions demonstrate positive learning potential, yet they do not consistently make reflective and pedagogical transformation explicit. Third, research on reflection provides evidence of its role in critical thinking and pedagogical knowledge development, but reflection is generally examined independently from scientific literacy interventions. Finally, EXARIS offers a structured sequence incorporating reflection and communication, although its initial empirical application has remained within elementary-school learning. **Table 1** compares recent research on pre-service teachers' scientific literacy, identifying contributions and limitations that motivate the present study.

Table 1

Recent research and positioning of the present study

Study	Context / Participants	Focus or approach	Main Contribution	Limitation Relevant to the Present Study
Kinyota & Kajungu (2024)	Pre-service teachers	Scientific literacy conceptions and curriculum	Identified dominant content, procedural, and utility orientations	Diagnostic; no instructional intervention
Bennion & Davis (2024)	Pre-service elementary teachers	Engagement in science practices	Demonstrated variation in engagement with authentic scientific practices	Did not examine an integrated scientific literacy model
Delgado-Iglesias et al. (2024)	579 pre-service primary teachers	Inquiry preparation	Inquiry competence improved following instructional experience	Didactic transfer remained a challenge
Badaruddin et al. (2024)	56 pre-service elementary teachers	STEM-integrated project-based learning	Reported positive improvement in scientific literacy	Primarily focused on quantitative outcomes
Arias et al. (2024)	Pre-service elementary teachers across three universities	Reflective rehearsal and classroom enactment	Showed the value of reflection for evidence-based noticing and scientific sense-making	Reflection was not embedded within a scientific literacy intervention
Saribas (2025)	51 pre-service elementary teachers	Scientific literacy through environmental issues	Revealed the importance of linking scientific issues with curricular and pedagogical reasoning	Many participants showed limited curricular connections
Prayogi et al. (2025)	Pre-service science teachers	Reflective scientific inquiry	Structured reflection strengthened critical thinking	Did not focus specifically on elementary teacher education or scientific literacy outcomes
Januar et al. (2025)	Grade 6 elementary students	EXARIS learning model	Developed and evaluated EXARIS for scientific and digital literacy	Model was evaluated with elementary pupils rather than pre-service teachers
Present study	Pre-service elementary teachers at UNP, UNNES, and UPI	EXARIS-PBL; sequential exploratory mixed methods	Connects problem exploration, evidence analysis, reflection, pedagogical connection, and scientific communication	Extends EXARIS into teacher education and examines outcomes and learning processes across institutional contexts

The state of the art therefore suggests that the unresolved issue is not whether problem-centered learning, inquiry, or reflection can independently contribute to learning. Rather, the remaining challenge concerns how these processes can be organized coherently for pre-service elementary teachers whose scientific learning must also develop into pedagogically meaningful understanding. Within the recent literature reviewed for this study, no empirical work was identified that examines EXARIS integrated with PBL for pre-service elementary teachers

while simultaneously investigating scientific literacy outcomes and the learning processes underlying those outcomes across multiple institutional contexts.

The present study addresses this space by extending EXARIS from elementary-school instruction into pre-service elementary teacher education and embedding it within a PBL environment. Its positioning is therefore based on three linked developments: the transition from scientific literacy as an assessed competence toward scientific literacy as professional preparation; the movement from problem solving toward explicit reflection and pedagogical meaning-making; and the examination of a common learning framework within different institutional environments through complementary quantitative and qualitative evidence.

METHODOLOGY

Research design

This study employed a sequential exploratory mixed methods design to develop, implement, and evaluate the EXARIS-PBL model for strengthening scientific literacy among pre-service elementary teachers. A sequential exploratory design was selected because the study began with qualitative exploration to understand contextual learning conditions, followed by model refinement, empirical implementation, and integration of quantitative and qualitative evidence (Creswell & Plano Clark, 2025).

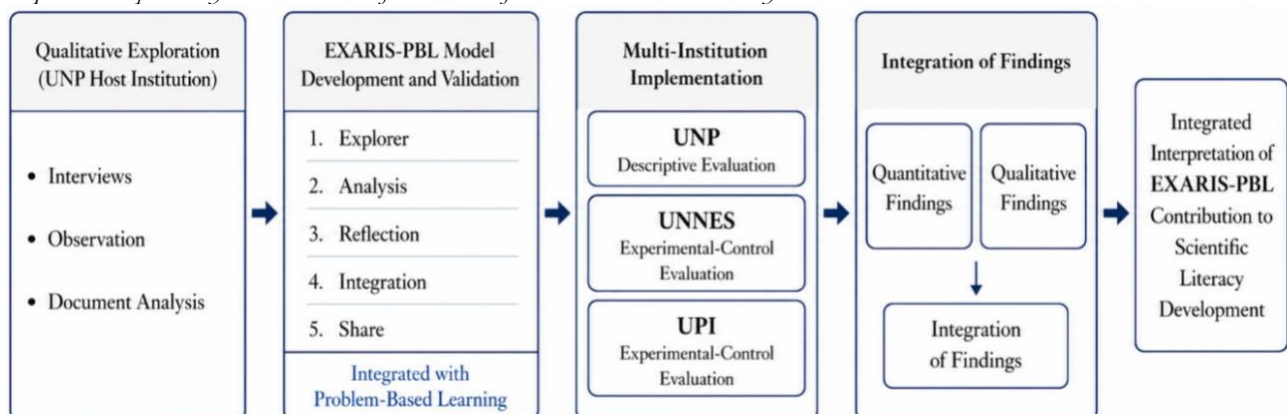
The research process consisted of four interconnected phases: (1) qualitative exploration, (2) EXARIS-PBL model development and expert validation, (3) multi-institution implementation with context-specific evaluation procedures, and (4) integration of quantitative and qualitative findings.

The qualitative exploration phase was conducted at Universitas Negeri Padang (UNP) as the host institution. This phase aimed to identify students' scientific literacy challenges, learning experiences, and contextual factors influencing science learning. Findings obtained from interviews, classroom observations, and document analysis were used to refine the EXARIS-PBL model, instructional materials, and research instruments.

The refined EXARIS-PBL model was subsequently implemented across three institutional contexts: Universitas Negeri Padang (UNP), Universitas Negeri Semarang (UNNES), and Universitas Pendidikan Indonesia (UPI). Because each institution had different implementation characteristics and evaluation structures, institution-specific evaluation approaches were applied. UNP was evaluated through a descriptive pretest-posttest evaluation without a comparison group, whereas UNNES and UPI employed experimental-control group comparisons. The overall research design and implementation framework are presented in [Figure 1](#).

Figure 1

Sequential exploratory mixed methods framework of the EXARIS-PBL study across three institutional contexts



Research context and participants

The study involved undergraduate students enrolled in Elementary School Teacher Education (PGSD) programs at three Indonesian universities: Universitas Negeri Padang (UNP), Universitas Negeri Semarang (UNNES), and Universitas Pendidikan Indonesia (UPI).

UNP served as the host institution responsible for the initial exploration, model development, expert validation, and implementation evaluation of the EXARIS-PBL model. UNNES and UPI served as partner institutions where the developed model was implemented within different academic contexts.

Participants were selected using purposive sampling based on their enrollment in elementary science education courses and their relevance to the research objectives. Because the study was conducted in authentic classroom environments, existing classroom structures were maintained rather than applying individual random assignment. The study involved 227 pre-service elementary teachers across the three institutions. At UNP, 28 students participated in the model development and implementation evaluation. At UNNES, 43 students were assigned to

the experimental group and 42 to the control group. At UPI, 57 students participated in the experimental group and 57 in the control group.

This approach enabled the evaluation of EXARIS-PBL within realistic educational settings while acknowledging the characteristics of classroom-based intervention research. [Table 2](#) summarizes the research roles and evaluation designs at UNP, UNNES, and UPI.

Table 2

Research context and evaluation approach

Institution	Research Role	Evaluation Approach
UNP	Host institution; model implementation	Descriptive pretest-posttest evaluation without a comparison group
UNNES	Partner institution	Experimental-control comparison
UPI	Partner institution	Experimental-control comparison

Ethical Consideration

Ethical considerations were addressed throughout the research process. Before data collection, participants were informed about the objectives, procedures, and academic purposes of the study. Participation was voluntary, and participants were informed that they could withdraw from the study at any time without academic consequences. Participants' identities and personal information were kept confidential, and the collected data were used solely for research and publication purposes.

EXARIS-PBL implementation procedure

The EXARIS-PBL model integrates the EXARIS learning sequence Explorer, Analysis, Reflection, Integration, and Share with Problem-Based Learning principles.

The intervention was implemented through six instructional meetings within the science learning context for pre-service elementary teachers. Each meeting followed the core principles of EXARIS-PBL while allowing contextual adaptation according to institutional characteristics.

The learning process was structured around contextual scientific problems that encouraged students to explore phenomena, formulate scientific questions, analyze evidence, reflect on reasoning processes, integrate scientific concepts with educational contexts, and communicate findings through collaborative scientific discussions. [Table 3](#) outlines the five EXARIS-PBL stages, learning activities, and intended learning outcomes.

Table 3

EXARIS-PBL learning procedure

Stage	Learning Process	Intended Learning Process
Explorer	Identifying contextual scientific phenomena and formulating problems	Scientific problem identification
Analysis	Examining information, evidence, and explanations	Scientific reasoning and evidence evaluation
Reflection	Evaluating understanding and reasoning processes	Metacognitive reflection
Integration	Connecting concepts with contextual applications	Knowledge application
Share	Communicating findings and scientific arguments	Scientific communication

The core learning sequence remained consistent across institutions, while implementation procedures were adapted according to institutional conditions.

Instruments and data collection

This study employed complementary quantitative and qualitative instruments to obtain comprehensive evidence regarding EXARIS-PBL implementation. The quantitative instrument consisted of a scientific literacy assessment developed based on scientific literacy indicators aligned with the PISA scientific literacy framework (OECD, 2019; OECD, 2023). The assessment consisted of 30 reasoned multiple-choice items designed to measure students' ability to explain scientific phenomena, interpret scientific evidence, analyze scientific information, and apply scientific knowledge in contextual situations.

Each item required students to select the most appropriate answer and provide a scientific justification. Responses were evaluated using an analytical scoring rubric that considered both answer accuracy and the quality of scientific reasoning. The obtained scores were converted into a 0–100 scale to facilitate interpretation of

students' scientific literacy achievement. Instrument quality was examined through expert judgment and construct validation. Reliability analysis was conducted using Cronbach's Alpha, and the instrument demonstrated excellent internal consistency (Cronbach's Alpha = 0.91).

Qualitative data were collected through semi-structured interviews, classroom observations, reflective journals, and student learning documents. These sources were used to examine students' experiences, engagement patterns, reflective processes, scientific reasoning development, and learning transformations during implementation.

Data analysis

Quantitative analysis

Quantitative data were analyzed according to the evaluation design and statistical characteristics of each institutional dataset. Descriptive statistics, including means and standard deviations, were calculated to summarize students' scientific literacy achievement. Prior to inferential analysis, the distribution and variance characteristics of the data were examined to determine the appropriate statistical procedures.

At UNP, quantitative data were analyzed descriptively because this institution served as the host site for model development and initial implementation evaluation. Changes between pretest and posttest scientific literacy scores were therefore interpreted as descriptive achievement patterns rather than as evidence of comparative effectiveness.

At UNNES, the experimental and control groups were compared using the Mann–Whitney U test because the data did not satisfy the assumptions required for parametric group comparison. At UPI, baseline equivalence between the experimental and control groups was examined using Welch's independent samples t-test. Posttest differences were subsequently analyzed using analysis of covariance (ANCOVA), with pretest scores included as a covariate to account for initial score variation between groups.

Qualitative analysis

Qualitative data from semi-structured interviews, classroom observations, reflective journals, and student learning documents were analyzed to identify recurring patterns related to students' learning experiences, reflective processes, scientific reasoning, pedagogical awareness, and scientific communication. Evidence from the different qualitative sources was examined comparatively to identify patterns that were consistently reflected across the implementation contexts. The resulting patterns were organized into broader themes that were used to explain the learning processes underlying the quantitative findings.

Integration of quantitative and qualitative findings

Integration of quantitative and qualitative findings was conducted during the interpretation phase by comparing quantitative achievement patterns with qualitative themes identified from interviews, classroom observations, reflective journals, and student learning documents. The integration focused on examining how the qualitative evidence helped explain variations in scientific literacy outcomes across institutional contexts. Quantitative findings provided evidence of achievement patterns, while qualitative findings provided contextual explanations related to inquiry, reflection, pedagogical awareness, collaboration, and scientific communication. The integrated interpretation was then used to identify how EXARIS-PBL operated across the three institutional settings.

RESULTS

Quantitative findings

The EXARIS-PBL model was implemented across three institutional contexts: Universitas Negeri Padang (UNP), Universitas Negeri Semarang (UNNES), and Universitas Pendidikan Indonesia (UPI). Following the sequential exploratory mixed methods design, quantitative evaluation procedures were adapted according to the characteristics of each institutional context. UNP was evaluated through a descriptive pretest-posttest evaluation without a comparison group, whereas UNNES and UPI employed experimental-control group comparisons. The distribution of participants and evaluation characteristics are summarized in [Table 4](#).

Table 4*Institutional context and evaluation characteristics*

Institution	Evaluation Design	Group	n
UNP	Descriptive pretest-posttest evaluation without a comparison group	EXARIS-PBL implementation	28
UNNES	Experimental-control comparison	Experimental	43
UNNES	Experimental-control comparison	Control	42
UPI	Experimental-control comparison	Experimental	57
UPI	Experimental-control comparison	Control	57

Quantitative findings were interpreted according to the evaluation design applied at each institution. During the development evaluation phase at UNP, the implementation of EXARIS-PBL showed an improvement in students' scientific literacy scores, increasing from 71.13 (SD = 8.44) to 82.30 (SD = 7.81), representing a descriptive score change of 11.17 points. Since UNP functioned as the host institution for model development and did not employ a comparative control group design, these findings were interpreted descriptively rather than as comparative effectiveness evidence.

The effectiveness evaluation was conducted at partner institutions, namely UNNES and UPI, using experimental-control comparisons. At UNNES, the experimental group increased from 77.13 to 86.15, representing a score change of 9.02 points, while the control group increased from 75.11 to 82.54, representing a score change of 7.43 points. At UPI, the experimental group increased from 77.72 to 80.48, representing a score change of 2.76 points, whereas the control group decreased from 82.03 to 77.69, representing a score change of -4.34 points. As shown in [Table 5](#), scientific literacy scores increased in the EXARIS-PBL groups across the three institutions, although the magnitude of improvement varied according to institutional context and evaluation design.

Table 5*Descriptive statistics of scientific literacy outcomes across institutions*

Research Phase	Institution	Group	n	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD	Score Change
Development Evaluation	UNP	EXARIS-PBL Implementation	28	71.13	8.44	82.30	7.81	11.17
Effectiveness Evaluation	UNNES	Experimental	43	77.13	3.65	86.15	3.96	9.02
Effectiveness Evaluation	UNNES	Control	42	75.11	7.17	82.54	7.10	7.43
Effectiveness Evaluation	UPI	Experimental	57	77.72	15.97	80.48	14.64	2.76
Effectiveness Evaluation	UPI	Control	57	82.03	15.60	77.69	15.10	-4.34

Note: UNP data represent the development evaluation phase of EXARIS-PBL implementation. The score change is presented descriptively to describe achievement patterns during model development and is not interpreted as comparative effectiveness evidence. Effectiveness evaluation was conducted only at UNNES and UPI using experimental-control comparisons.

The UNP evaluation provided evidence of students' scientific literacy achievement following the implementation of the EXARIS-PBL model. As UNP served as the host institution for model development, the findings were interpreted descriptively to illustrate students' achievement patterns after implementation. The observed increase from 71.13 (SD = 8.44) to 82.30 (SD = 7.81) indicates positive changes in students' scientific literacy performance; however, these findings are not interpreted as comparative effectiveness evidence because UNP did not employ an experimental-control comparison design.

The effectiveness evaluation was subsequently conducted at partner institutions, namely UNNES and UPI, using experimental-control comparisons. At UNNES, the experimental group demonstrated higher post-intervention scientific literacy achievement compared with the control group. The Mann-Whitney U test indicated a significant difference favoring the EXARIS-PBL group ($Z = -3.095$, $p = 0.002$), with an effect size of 0.490.

At UPI, baseline equivalence analysis was conducted to examine whether the experimental and control groups had comparable initial scientific literacy levels before the intervention. Welch's independent samples t-test showed no significant difference between groups at pretest ($t = -1.458$, $df = 111.94$, $p = 0.148$), indicating comparable initial conditions. Further analysis using ANCOVA, with pretest scores included as a covariate, showed that the adjusted posttest difference between groups was not statistically significant ($F = 1.009$, $p = 0.317$, partial $\eta^2 = 0.009$). These findings suggest that the effectiveness of EXARIS-PBL varied depending on institutional context

and implementation conditions. **Table 6** summarizes the inferential statistical findings, indicating a significant difference favoring the EXARIS-PBL group at UNNES, while the adjusted posttest difference at UPI was not statistically significant.

Table 6

Summary of inferential analysis across effectiveness evaluation sites

Institution	Statistical Procedure	Main Result
UNNES	Mann–Whitney U test	Significant difference favoring the EXARIS-PBL group ($Z = -3.095$, $p = 0.002$), effect size = 0.490
UPI	Welch’s independent samples t-test and ANCOVA	No significant baseline difference and no significant adjusted posttest difference between groups

Qualitative findings

Qualitative analysis was conducted to explain the learning processes underlying quantitative outcomes. Data from interviews, classroom observations, reflective journals, and student learning documents generated three interconnected themes:

1. progressive pedagogical awareness;
2. professional teacher identity development;
3. epistemic collaboration and scientific communication.

Table 7 presents the three qualitative themes identified during implementation, together with their evidence sources and representative student responses illustrating pedagogical awareness, professional teacher identity development, and epistemic collaboration.

Table 7

Qualitative themes and representative evidence

Theme	Evidence Source	Representative Student Response
Progressive pedagogical awareness	Interviews, reflective journals, observations	“After the reflection process, I started thinking about how elementary students might misunderstand the concept and how I could help them understand it better.” (UNNES-S07)
Professional teacher identity development	Interviews, student documents	“Science learning is not only about knowing the correct answer. As a future teacher, I need to think about how students can discover and explain scientific ideas.” (UPI-S12)
Epistemic collaboration	Classroom observations, discussion records	“Different opinions could be accepted when supported by scientific evidence.” (UNP-S05)

The first theme reflected students’ transition from understanding scientific concepts toward deeper pedagogical reasoning. Students increasingly considered how scientific concepts could be explained effectively to elementary students and how misconceptions could be addressed during learning.

The second theme indicated changes in students’ professional teacher identity. Students began viewing scientific knowledge not only as content to be mastered but also as knowledge that must be transformed into meaningful learning experiences.

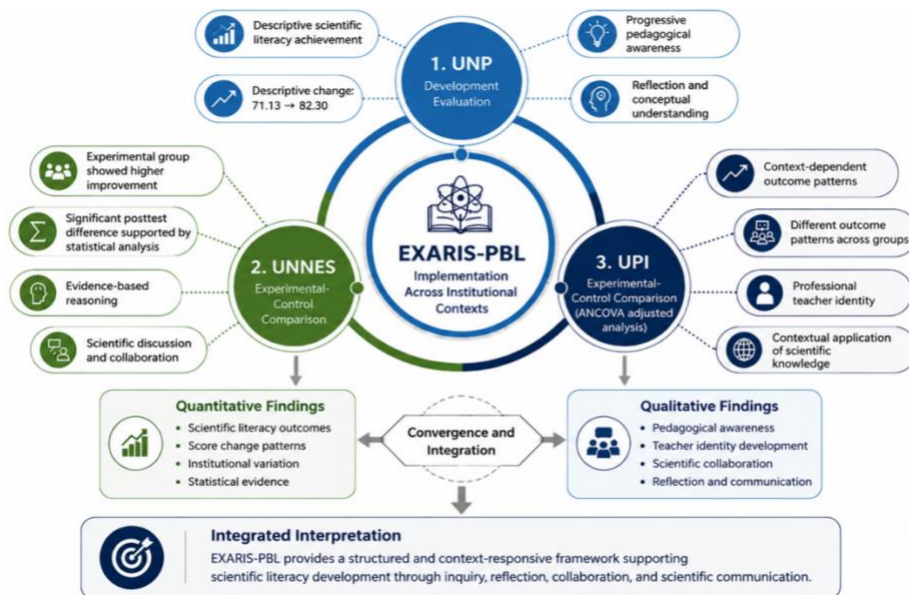
The third theme demonstrated changes in collaborative learning processes. Students increasingly engaged in evidence-based discussions, negotiated different perspectives, and developed scientific arguments through peer interaction.

Integration of Quantitative and Qualitative Findings

The integration phase connected quantitative patterns with qualitative themes to generate a comprehensive interpretation of EXARIS-PBL implementation.

The integrated findings showed that quantitative outcomes were supported by qualitative evidence describing the learning mechanisms underlying EXARIS-PBL implementation. While achievement patterns varied across institutional contexts, students consistently demonstrated development in inquiry processes, reflective thinking, collaboration, and scientific communication.

Figure 2 provides a joint display of the quantitative and qualitative findings across the three institutional contexts, illustrating variations in scientific literacy outcomes alongside common developments in reflection, pedagogical awareness, collaboration, and scientific communication.

Figure 2*Joint display of quantitative and qualitative findings across institutional contexts*

DISCUSSION

The findings indicate that EXARIS-PBL can support the development of scientific literacy among pre-service elementary teachers by connecting scientific inquiry, evidence analysis, reflection, conceptual understanding, and scientific communication within a structured learning process. The contribution of the study extends beyond differences in learning outcomes because the qualitative findings provide insight into how future teachers construct, reconsider, and communicate scientific understanding. Across institutional contexts, the quantitative patterns were accompanied by developments in pedagogical awareness, professional teacher identity, and evidence-based collaboration, suggesting that scientific literacy development involves both cognitive outcomes and changes in how learners participate in scientific practices.

This interpretation is consistent with contemporary conceptions of scientific literacy as a multidimensional educational outcome. Roy et al. (2025) showed that recent scientific literacy research increasingly emphasizes the application of scientific knowledge, engagement with scientific practices, problem solving, and meaningful use of science rather than factual knowledge alone. From this perspective, scientific literacy develops through opportunities to work with problems and evidence, construct explanations, and apply scientific understanding. EXARIS-PBL operationalizes these processes through its Explorer, Analysis, Reflection, Integration, and Share stages.

The findings can also be interpreted in relation to recent developments in Problem-Based Learning (PBL). Although PBL provides a strong basis for engaging learners with complex problems, its effectiveness depends on how problem-solving activities are organized. Yu & Zin (2023) found that adaptations of PBL that incorporated explicit reasoning processes and complementary pedagogical strategies were particularly relevant to the development of critical thinking. This supports the rationale underlying EXARIS-PBL: presenting learners with a meaningful problem initiates learning, but additional structure is required to direct attention toward evidence evaluation, reflection, conceptual connection, and communication.

EXARIS-PBL therefore extends the problem-centered learning process by explicitly organizing what occurs between encountering a scientific problem and communicating an evidence-based explanation. Explorer establishes the problem space, while Analysis directs attention toward information and evidence. Reflection encourages learners to reconsider how their explanations were constructed, Integration connects scientific understanding with contextual and pedagogical meaning, and Share requires learners to articulate and negotiate their explanations. The model consequently does not replace the principles of PBL; rather, it provides a structured progression through which problem solving can be connected with scientific and pedagogical reasoning.

Reflection appears particularly important in explaining the qualitative developments observed in this study. Students increasingly moved from viewing scientific knowledge primarily as content to considering how such knowledge could be explained, interpreted, and taught. Michalsky (2024) found that metacognitive scaffolding enhanced pre-service science teachers' capacity to regulate their learning, reflect on learning events, and design higher-order thinking tasks. This suggests that reflection becomes especially productive when learners are explicitly prompted to examine the reasoning underlying both their understanding and their future instructional decisions.

Recent work on teacher preparation provides further support for this interpretation. Fono & Zohar (2025) found that pre-service and novice teachers can develop knowledge for metacognitive instruction when they receive deliberate preparation, although translating this knowledge into sophisticated classroom practice remains challenging. Reflection in EXARIS-PBL should therefore not be understood as a concluding activity following problem solving. It functions as a mechanism through which scientific experience can be reconsidered and gradually transformed into professionally relevant understanding.

The importance of structured guidance is also evident in recent inquiry research. de Jong et al. (2024) argue against treating inquiry and direct instruction as competing alternatives and instead emphasize the careful combination of instructional strategies according to learners, tasks, and contexts. Similarly, Sasse et al. (2025) demonstrated that responsive teacher scaffolding during inquiry can influence students' procedural learning. These findings suggest that learner agency does not require the absence of instructional support; rather, productive inquiry depends on guidance that directs learners' attention without eliminating opportunities for investigation.

EXARIS-PBL addresses this issue through an explicit learning progression. Explorer allows learners to engage with scientific problems, but this exploration is followed by Analysis and Reflection before learners move toward contextual application and communication. The model can therefore be interpreted as a guided problem-centered framework in which learner agency is maintained while cognitive activities are progressively organized. This interpretation is consistent with Areepattamannil (2025) argument that effective guided inquiry requires attention to orchestration, assessment, discourse, and learner support rather than the simple frequency of inquiry activities.

The importance of explicit inquiry experiences is also supported by recent research with pre-service science teachers. Erenler et al. (2025) found that argument-driven inquiry activities improved prospective science teachers' understanding of several dimensions of scientific inquiry, particularly their recognition of multiple methods of investigation and distinctions between data and evidence. Although EXARIS-PBL is not an argumentation model, this evidence reinforces the importance of making evidence evaluation and scientific reasoning explicit within inquiry-oriented learning.

Scientific communication represents another mechanism through which the present findings can be interpreted. Students increasingly participated in evidence-based discussions and negotiated alternative perspectives during collaborative learning. Haridza & Ding (2025), using large-scale science education data, reported a positive relationship between instructional practices that require evidence-based explanations and students' scientific reasoning performance. Such evidence supports the Share stage of EXARIS-PBL, in which learners are expected to articulate explanations and make the reasoning supporting their conclusions visible.

Communication is particularly significant in teacher education because future teachers must learn not only to understand scientific ideas but also to explain them responsively. Kulgemeyer & Geelan (2024) conceptualize instructional explanation as a core practice of science teachers and emphasize that effective explanations involve interaction with learners rather than one-directional transmission. This professional dimension is highly relevant to the qualitative finding of progressive pedagogical awareness, in which participants increasingly considered how scientific concepts might be understood by elementary students.

Mercier & Hinman (2025) provide further evidence that the interpretation of children's scientific explanations constitutes an important element of pre-service teacher preparation. Their study showed that prospective teachers' ways of noticing and interpreting elementary students' communication of scientific ideas can develop through repeated reflective experiences. In the context of EXARIS-PBL, the movement from Reflection to Integration and Share may therefore have significance beyond students' own scientific communication: it can also encourage future teachers to think about how scientific ideas are expressed, interpreted, and supported in elementary classrooms.

The collaborative dimension of the findings is similarly important. The qualitative theme of epistemic collaboration indicates that students increasingly negotiated perspectives and evaluated ideas through interaction with peers. Chen & Chen (2025), in a systematic review of technology-enhanced collaborative inquiry, found positive outcomes for content learning, inquiry processes, and scientific practices when collaboration was supported by appropriate activities and tools. Their synthesis reinforces the view that collaboration becomes educationally productive when learners are required to work jointly with evidence and explanations rather than simply divide tasks.

Evidence from higher education also points in this direction. Elmi (2025) reported that inquiry-based discussions supported by collaborative platforms can promote meaningful dialogue, engagement with scientific topics, and collaborative reasoning. While EXARIS-PBL does not depend on a particular technology, the underlying principle is comparable: interaction becomes a mechanism for learning when students are expected to articulate ideas, consider peer perspectives, and refine understanding. The Share stage therefore serves not merely as dissemination of completed answers but as an opportunity for further knowledge construction.

The qualitative development of professional teacher identity provides another important interpretation of the findings. Students increasingly described scientific learning in relation to their future responsibilities as teachers

rather than solely as university students completing science coursework. Zhai et al. (2024), in a scoping review of science teacher identity research, identified teacher preparation experiences, disciplinary and pedagogical knowledge, interaction with others, and reflective processes as important influences on the development of science teacher identity. EXARIS-PBL appears to create conditions in which scientific learning and professional meaning can intersect through repeated opportunities to investigate, reflect, connect, and communicate.

This interpretation is also consistent with evidence concerning inquiry experiences in initial teacher education. Contreras et al. (2024) found that an inquiry-based practicum increased the complexity of pre-service teachers' understandings of inquiry, particularly when the inquiry process was systematically organized into identifiable phases. The finding is relevant to EXARIS-PBL because its stages make the learning progression visible. Students are not simply asked to "do inquiry"; they move through defined processes that provide opportunities to recognize how scientific investigation, reflection, and application are connected.

Contextual scientific experiences may further support the transition from disciplinary understanding toward pedagogical reasoning. Park et al. (2024), for example, showed that engaging pre-service science teachers with a complex disaster case enabled them to identify relationships among science, technology, society, and potential classroom applications, although substantial instructional support remained necessary. This highlights an important point for EXARIS-PBL: meaningful contextual problems can provide powerful learning opportunities, but their pedagogical value depends on how students are guided to analyze and reinterpret them.

The multi-institution implementation of EXARIS-PBL adds another dimension to the findings. Quantitative outcomes did not display identical patterns across UNP, UNNES, and UPI. The strongest statistical evidence was observed at UNNES, whereas the UPI implementation showed a modest descriptive improvement in the intervention group without statistically significant adjusted differences between groups. UNP, which employed a different evaluation structure, provided evidence of post-intervention scientific literacy achievement rather than a causal comparison. These differences reinforce the need to interpret EXARIS-PBL as a framework operating within educational contexts rather than as a fixed intervention expected to generate identical outcomes in every setting.

Implementation research supports this interpretation. Ryan et al. (2024) emphasize that the scaling and transfer of educational interventions require consideration of context, barriers, facilitators, and implementation outcomes rather than intervention effectiveness alone. Their review indicates that understanding how an intervention operates across settings is essential when educational innovations are transferred beyond their original context.

Dowd (2024) similarly argues that implementation research can contribute to understanding what works, where, and for whom by examining how educational interventions are adapted to local conditions. The variation observed across the three institutions in this study should therefore not automatically be interpreted as inconsistency in the EXARIS-PBL framework. Instead, it illustrates how a common instructional structure may interact with student characteristics, classroom organization, instructional support, and institutional environments.

This contextual interpretation is especially important because the present study intentionally employed context-specific evaluation procedures. UNP served as the host institution and was evaluated through a descriptive pretest-posttest evaluation without a comparison group, whereas UNNES and UPI employed experimental-control comparisons. Consequently, findings across institutions should be regarded as complementary evidence rather than as a direct ranking of institutional effectiveness. The mixed methods design further allows quantitative patterns to be considered alongside qualitative evidence concerning how students experienced inquiry, reflection, collaboration, communication, and professional learning.

This study has several limitations that should be considered when interpreting the findings. First, the implementation of EXARIS-PBL was conducted across different institutional contexts, which may have influenced the magnitude of the observed outcomes. Variations in institutional characteristics, learning environments, and implementation conditions may contribute to differences in effectiveness patterns among universities. Second, the UNP development evaluation did not employ a comparative control group design; therefore, its findings were interpreted descriptively and should not be considered as evidence of causal effectiveness. Third, this study evaluated immediate learning outcomes, and future research should examine the long-term impact of EXARIS-PBL through longitudinal studies and delayed assessments.

Overall, the findings suggest that strengthening scientific literacy among pre-service elementary teachers requires more than exposure to scientific problems. Learners require structured opportunities to examine evidence, reconsider reasoning, connect scientific understanding with pedagogical meaning, and communicate explanations through interaction with others. EXARIS-PBL provides one framework for organizing these processes through Explorer, Analysis, Reflection, Integration, and Share. The study therefore positions scientific literacy development as both a process of scientific learning and an important component of professional preparation for future elementary teachers.

CONCLUSION

This study advances science teacher education research by demonstrating how an instructional framework can integrate scientific literacy development with the professional preparation of pre-service elementary teachers. The findings highlight that scientific literacy development involves more than acquiring scientific knowledge; it requires opportunities for learners to engage in inquiry, evidence analysis, reflection, conceptual integration, and scientific communication as interconnected learning processes.

The contribution of this study lies in the development and evaluation of EXARIS-PBL as a context-responsive framework that extends conventional problem-based learning. Rather than focusing solely on problem solving and learning outcomes, EXARIS-PBL provides a structured learning pathway that connects exploration, evidence-based analysis, reflection, conceptual integration, and scientific communication. This integration contributes theoretically by explaining how scientific literacy development can occur through both cognitive engagement and pedagogical transformation, while also providing practical implications for science teacher education.

The findings suggest that EXARIS-PBL has potential value for science teacher education programs by supporting the development of scientific reasoning and professional teacher identity formation. The effectiveness patterns, however, varied across institutional contexts. The strongest statistical evidence was observed at UNNES, while the UPI implementation showed non-significant differences after controlling for baseline conditions. Meanwhile, UNP provided descriptive evidence of students' achievement development during the model implementation phase. These findings indicate that EXARIS-PBL should be understood as an adaptable instructional framework whose implementation outcomes may depend on institutional characteristics, learning environments, and contextual conditions.

Beyond the immediate research context, this study contributes to the broader understanding that educational innovations should be implemented as flexible frameworks rather than fixed instructional procedures. The multi-institution perspective emphasizes the importance of considering contextual factors when designing, implementing, and scaling instructional models in teacher education.

Future research should extend this work by examining the long-term impact of EXARIS-PBL through longitudinal designs, delayed assessments, and broader implementation across diverse educational settings. Further investigation is also needed to explore how teacher support, institutional readiness, classroom conditions, and implementation fidelity influence the scalability and sustainability of the model.

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Ethical statement

This study was conducted in accordance with ethical principles for educational research involving human participants. All participants were informed about the research objectives, procedures, and academic purposes before data collection. Participation was voluntary, and participants had the right to withdraw at any time without academic consequences. The confidentiality of participants' identities and personal information was maintained throughout the research process. All collected data were used exclusively for research and academic publication purposes.

Competing interests

The authors declare that they have no competing interests.

Author contributions

Y.F contributed to data collection and assembly. Y.H was responsible for research conceptualization and design. P.S contributed to data analysis and interpretation. G.H was responsible for manuscript writing. E.S contributed to critical revision of the manuscript. H.H contributed to the final approval of the article. M.Z

contributed to data analysis, interpretation, and critical revision of the manuscript. All authors have read and approved the final version of the manuscript.

Data availability

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request, subject to ethical considerations and participant confidentiality.

AI disclosure

Generative AI tools were used to assist with academic language refinement and manuscript editing. The authors reviewed the AI-assisted content and take full responsibility for the final manuscript.

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