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Developing and Validating an Inquiry-Based Science Instructional Design to Foster Scientific Literacy among Elementary School Students

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Abstract: *Scientific literacy is essential for students to explain scientific phenomena, evaluate evidence, and make informed decisions. However, Indonesian students continue to demonstrate low scientific literacy, as reflected in PISA 2022, highlighting the need for stronger inquiry-oriented science instruction at the elementary level. Although inquiry-based learning (IBL) supports scientific literacy development, limited attention has been given to systematically developing and validating instructional designs aligned with scientific literacy competencies. This study aimed to develop and evaluate an inquiry-based science instructional design using Educational Design Research (EDR). The study involved four iterative phases: analysis and exploration, design and construction, evaluation and reflection, and design refinement. Participants comprised one expert validator, one teacher, and 32 elementary students. Data were collected through expert validation, scientific literacy tests, and student response questionnaires. The design achieved 93.33% validity and 86.40% student responses. Scientific literacy scores increased from 58.84 to 84.31, with a significant pretest–posttest difference (t(31) = 16.82, p < .001) and an overall N-gain of 0.69. These findings provide preliminary evidence that systematically designed IBL can support scientific literacy development in elementary science education.*

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INTRODUCTION

Scientific literacy is increasingly recognized as a fundamental competence for enabling individuals to understand scientific phenomena, evaluate evidence, and make informed decisions in complex societal contexts. Contemporary conceptions of scientific literacy extend beyond the acquisition of scientific knowledge to include the ability to explain phenomena scientifically, evaluate and design scientific inquiry, and interpret scientific data and evidence (De Regt & Dieks, 2005; Musonif, Novikasari, et al., 2026; OECD, 2023; Ramadona et al., 2026). These competencies require learners to engage actively in scientific practices, including questioning, investigating, interpreting evidence, and constructing scientifically justified explanations. Consequently, science education needs to provide learning experiences that connect conceptual understanding with authentic scientific practices, particularly from the early stages of formal education (Azis et al., 2026; Az-zahra et al., 2026; Martin, 2019; Musonif et al., 2026).

The need to strengthen scientific literacy is particularly relevant in Indonesia. The Programme for International Student Assessment (PISA) 2022 reported that Indonesian students obtained a science score of 383, declining from 396 in 2018 and remaining substantially below the OECD average (OECD, 2023). This performance indicates persistent challenges in applying scientific knowledge and reasoning to authentic problems. Previous research has similarly reported limitations in Indonesian students' scientific literacy and scientific reasoning, suggesting that science instruction needs to provide greater opportunities for students to engage with evidence, inquiry, and higher-order scientific thinking (Alvarez-Tinajero et al., 2025; Musonif et al., 2026; Pamela et al., 2026). These concerns are particularly important at the elementary level, where students begin to develop foundational abilities to observe phenomena, formulate questions, investigate problems, and interpret evidence.

The development of scientific literacy, however, is influenced not only by students' conceptual knowledge but also by the quality of classroom instruction. Teacher-centered practices and an excessive emphasis on factual knowledge may provide limited opportunities for students to engage in authentic scientific practices and evidence-based reasoning (Council, 2012; OECD, 2023; Ramli et al., 2022; Woods & Copur-Gencturk, 2024). Accordingly, improving scientific literacy requires instructional designs that systematically connect scientific concepts with opportunities for students to participate in inquiry processes. Among the pedagogical approaches available for this purpose, inquiry-based learning (IBL) is particularly relevant because it engages students in scientific practices such as asking questions, planning investigations, collecting and interpreting evidence, and constructing explanations (Musonif & Azis, 2026; Rizal et al., 2026; Wu & Hsieh, 2006). National Research Council, 2012). Empirical studies have also reported positive associations between inquiry-oriented science instruction and students' scientific literacy, science process skills, and scientific reasoning (Azis et al., 2026; Eymur & Çetin, 2024; Harefa, 2023; Musonif et al., 2026).

Nevertheless, adopting inquiry-based learning does not automatically ensure the development of scientific literacy. Inquiry activities in classroom practice may remain fragmented and concentrate primarily on hands-on experimentation without systematically supporting question formulation, evidence interpretation, and scientific argumentation (Morris, 2025). Such implementation may allow students to conduct experiments without engaging fully in the reasoning processes that characterize scientific inquiry. Thus, the critical issue is not simply whether inquiry-based learning is used, but how inquiry processes are systematically organized within instructional design to support the competencies targeted by scientific literacy frameworks. Recent research similarly emphasizes the importance of instructional quality, scaffolding, and the deliberate organization of inquiry processes in determining the educational value of inquiry-based science learning (Harefa, 2023; OECD, 2023).

Despite the growing literature on inquiry-based learning and scientific literacy, three limitations remain relevant. First, research on inquiry and scientific literacy has more frequently examined secondary education, while comparatively less attention has been given to the elementary level, where the foundations of scientific reasoning are established. Second, existing studies have often focused on the learning effects of inquiry-based models rather than on the systematic development and validation of instructional designs that organize inquiry as a coherent learning sequence. Third, less attention has been given to how specific inquiry processes can be deliberately connected to the competencies of scientific literacy, including explaining phenomena, designing and evaluating inquiry, and interpreting scientific evidence. These limitations indicate a need for an instructional design that does not treat inquiry as a collection of experimental activities but as an integrated process through which students progressively develop scientific reasoning.

Addressing these gaps, the present study develops an inquiry-based science instructional design that systematically integrates six interconnected processes: question formulation, investigation planning, data collection, evidence interpretation, scientific argumentation, and reflective evaluation. Rather than positioning inquiry-based learning merely as a strategy for improving test performance, the proposed design connects each inquiry process with the scientific literacy competencies articulated in the OECD framework. The study contributes conceptually by emphasizing instructional sequencing as a mechanism linking scientific inquiry with scientific literacy development, methodologically by developing and validating the design through an Educational Design Research (EDR) process, and practically by providing elementary teachers with a structured framework for implementing inquiry-oriented science learning.

Accordingly, this study aims to: (1) develop an inquiry-based science learning design for elementary school students; (2) examine the validity and practicality of the developed instructional design; and (3) investigate the effectiveness of the instructional design in fostering elementary students' scientific literacy. The findings are expected to contribute to the theoretical advancement of inquiry-based science education in elementary contexts while providing educators with a valid, practical, and effective instructional design that supports the development of scientific literacy and responds to the continuing challenges identified in international assessments.

THEORETICAL BACKGROUND

Scientific Literacy

Scientific literacy is conceptualized as the ability to apply scientific knowledge and practices to explain phenomena, evaluate and design scientific inquiry, and interpret scientific data and evidence (Saifudin et al., 2026; Yacoubian, 2018). The PISA 2022 Science Framework identifies three interrelated competencies: (1) explaining phenomena scientifically, (2) evaluating and designing scientific inquiry, and (3) interpreting data and evidence scientifically (OECD, 2023). This conceptualization emphasizes that scientific literacy involves not only understanding scientific concepts but also engaging in the reasoning and practices through which scientific knowledge is generated and evaluated.

At the elementary level, these competencies are developed through repeated opportunities to observe phenomena, formulate questions, investigate problems, interpret evidence, and communicate explanations. Therefore, science instruction should provide structured learning experiences that connect conceptual understanding with authentic scientific practices rather than relying primarily on knowledge transmission. This orientation is particularly relevant to the present study because the proposed instructional design uses scientific inquiry as the primary pedagogical process for developing scientific literacy.

Inquiry-Based Learning

Inquiry-Based Learning (IBL) is grounded in constructivist learning theory, which views learning as an active process in which students construct understanding through interaction with phenomena and their learning environment (Fahrezi et al., 2026; Moemeke et al., 2025). In inquiry-oriented science learning, students engage in questioning, investigation, evidence-based reasoning, and reflection, while teachers facilitate and scaffold the learning process.

The National Research Council (2012) describes scientific inquiry as involving interconnected practices such as asking questions, planning investigations, collecting evidence, interpreting data, constructing explanations, and communicating findings. Thus, IBL extends beyond hands-on experimentation and provides a structured pedagogical process through which students engage in authentic scientific practices. Empirical studies have reported positive effects of inquiry-oriented science instruction on scientific literacy and related scientific competencies, including among elementary students (Eymur & Çetin, 2024; Harefa, 2023; Hasanah et al., 2026; Musonif et al., 2026).

Despite these benefits, the implementation of IBL does not automatically ensure comprehensive scientific reasoning. Inquiry activities may become fragmented when classroom instruction emphasizes experimentation without adequately supporting question formulation, evidence evaluation, and scientific argumentation (Morris, 2025). Therefore, effective IBL requires instructional designs that organize inquiry processes coherently and provide explicit support for students throughout the inquiry cycle.

Inquiry-Based Learning as a Pedagogical Foundation for Scientific Literacy

The theoretical relationship between IBL and scientific literacy lies in their shared emphasis on active engagement in scientific practices. The three scientific literacy competencies identified by the OECD—explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence—require students to participate in processes that closely correspond to those emphasized in inquiry-based learning (OECD, 2023; Council, 2012; Musonif & Misbah, 2026).

Question formulation and investigation planning provide opportunities for students to engage in evaluating and designing scientific inquiry, while data collection and evidence interpretation support the interpretation of scientific data and evidence. Scientific argumentation and explanation construction further require students to connect evidence with scientific claims and explanations. Empirical research indicates that participation in inquiry-oriented learning can support scientific reasoning, evidence interpretation, and scientific literacy development (Eymur & Çetin, 2024; Harefa, 2023).

However, the relationship between IBL and scientific literacy depends on the coherence of the instructional sequence. When inquiry is reduced to isolated experimental activities, students may have insufficient opportunities to develop the reasoning processes required by scientific literacy. (Morris, 2025).

Conceptual Framework

This study conceptualizes inquiry-based instructional design as a pedagogical mechanism linking scientific inquiry processes with the development of scientific literacy. The proposed design integrates six interconnected stages: question formulation, investigation planning, data collection, evidence interpretation, scientific argumentation, and reflective evaluation.

These stages are theoretically aligned with the three scientific literacy competencies proposed by the OECD (2023). Question formulation and investigation planning primarily provide opportunities to develop evaluating and designing scientific inquiry. Data collection and evidence interpretation support interpreting data and evidence scientifically, while scientific argumentation and reflective evaluation provide opportunities to integrate evidence with scientific explanations and reasoning, thereby supporting explaining phenomena scientifically and the broader development of scientific literacy.

The conceptual framework therefore positions the six inquiry stages as a coherent learning sequence rather than as isolated classroom activities. Through repeated engagement in these processes, students are expected to connect conceptual knowledge, empirical evidence, and scientific reasoning. This theoretical alignment provides the basis for developing the instructional design and examining its validity, practicality, and preliminary potential to support scientific literacy among elementary school students.

METHODS

This study adopted an Educational Design Research (EDR) approach to develop and conduct an initial evaluation of an inquiry-based science learning design intended to foster scientific literacy among elementary school students. Educational Design Research was selected because it provides a systematic framework for bridging educational theory and classroom practice through iterative processes of design, implementation, evaluation, and refinement, while simultaneously generating theoretically informed instructional solutions (McKenney & Reeves, 2019). In contrast to conventional experimental studies that primarily examine causal relationships between variables, EDR emphasizes the development of educational innovations grounded in empirical evidence and theoretical principles. Accordingly, the present study sought not only to produce an inquiry-based instructional design but also to ensure that the developed design was pedagogically meaningful, practically applicable, and theoretically aligned with the competencies of scientific literacy proposed in the OECD science framework (OECD, 2023). The research was conducted through four interconnected phases consisting of analysis and exploration, design and construction, evaluation and reflection, and design refinement, in which findings from each phase informed subsequent revisions of the instructional design.

The study was conducted in one public elementary school in Indonesia involving one science teacher, one expert validator, and thirty-two elementary students who participated in the classroom implementation. The research setting was purposively selected because the school had implemented the national curriculum while simultaneously identifying the need to strengthen students' scientific literacy through inquiry-oriented instruction. During the preliminary phase, an extensive review of the literature concerning scientific literacy, inquiry-based learning, instructional design, and the OECD science framework was undertaken to establish the theoretical foundation of the learning design. This review was complemented by discussions with the classroom teacher to identify contextual instructional challenges, existing classroom practices, and students' learning characteristics. The findings from this exploratory stage served as the basis for designing an inquiry-oriented instructional framework that explicitly integrated the core scientific practices emphasized in contemporary science education.

The instructional design was subsequently constructed by integrating six interconnected inquiry processes, namely question formulation, investigation planning, data collection, evidence interpretation, scientific argumentation, and reflective evaluation. These inquiry processes were systematically aligned with the three dimensions of scientific literacy described in the OECD framework, namely explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting scientific data and evidence (OECD, 2023). The resulting instructional package consisted of lesson plans, student worksheets, learning scenarios, assessment procedures, and implementation guidelines designed to facilitate meaningful scientific inquiry within elementary science classrooms. Prior to classroom implementation, the instructional design underwent expert review to examine its content relevance, pedagogical coherence, inquiry integration, language clarity, and instructional feasibility. Recommendations emerging from the validation process were incorporated into the design before it was implemented by the classroom teacher during regular science instruction.

Data were collected from multiple sources to support a comprehensive evaluation of the developed instructional design. Scientific literacy was measured using a pretest–posttest instrument constructed according to the competency domains specified in the OECD science framework, whereas students' perceptions regarding the practicality of the instructional design were collected through a structured response questionnaire administered after implementation. Expert judgment was employed to evaluate the content validity and instructional quality of the developed design, while classroom observations and implementation notes were documented throughout the learning process to support reflective evaluation during the refinement phase. The effectiveness evaluation adopted a one-group pretest–posttest design as an initial pilot implementation intended to examine the feasibility of the instructional design before broader application in comparable educational contexts. The combination of expert evaluation, classroom implementation, student assessment, and learner feedback enabled methodological triangulation and strengthened the credibility of the evaluation process.

The collected data were analyzed using both descriptive and inferential statistical procedures. Expert validation and students' response questionnaires were analyzed descriptively using percentage scores to determine the validity and practicality of the instructional design. Students' scientific literacy achievement before and after implementation was summarized using descriptive statistics, including means and standard deviations, while improvements in learning outcomes were examined through paired-samples t-tests after verifying the assumption of normality. In addition, normalized gain (N-gain) scores were calculated to estimate the magnitude of students' scientific literacy improvement following participation in the inquiry-based learning activities. Throughout the research process, ethical principles were maintained by obtaining institutional approval from the participating school, ensuring voluntary participation of the classroom teacher and students, preserving participants' confidentiality, and using all collected data exclusively for academic research purposes. Collectively, these methodological procedures were intended to ensure the validity, transparency, and trustworthiness of the research findings while providing a rigorous evaluation of the developed inquiry-based science learning design.

RESULTS AND DISCUSSION

RESULTS

Expert Validation of the Inquiry-Based Science Learning Design

Before classroom implementation, the inquiry-based science learning design was evaluated by an expert to determine its pedagogical quality, instructional coherence, and alignment with the scientific literacy competencies proposed in the OECD framework. The validation process examined six major aspects, including learning objectives, content relevance, inquiry syntax, scientific literacy integration, language clarity, and instructional feasibility.

Table 1. Expert Validation of the Inquiry-Based Science Learning Design

Validation Aspect	Maximum Score	Obtained Score	Percentage (%)	Category
Learning objectives	20	19	95.00	Very Valid
Content relevance	20	18	90.00	Very Valid
Inquiry learning syntax	20	19	95.00	Very Valid
Scientific literacy integration	20	19	95.00	Very Valid
Language clarity	20	18	90.00	Very Valid
Instructional feasibility	20	19	95.00	Very Valid
Overall	120	112	93.33	Very Valid

The expert validation indicated that the developed instructional design achieved an overall validity score of 93.33%, which falls within the Very Valid category. The highest evaluations were obtained for the learning objectives, inquiry learning syntax, scientific literacy integration, and instructional feasibility, suggesting that the developed design successfully integrated inquiry activities with the intended scientific literacy competencies. Minor revisions were recommended regarding the clarity of instructional language and the contextualization of several learning activities. These suggestions were incorporated before classroom implementation.

Students' Responses toward the Inquiry-Based Learning Design

Following implementation, students completed a response questionnaire to evaluate the practicality of the developed learning design. The questionnaire examined students' perceptions of inquiry activities, scientific reasoning, classroom engagement, and overall learning experience.

Table 2. Students' Responses toward the Inquiry-Based Science Learning Design

Indicator	Mean	SD	Percentage (%)	Category
Understanding scientific phenomena	4.41	0.42	88.20	Very Good
Conducting scientific inquiry	4.36	0.45	87.20	Very Good
Interpreting scientific evidence	4.24	0.48	84.80	Very Good
Scientific argumentation	4.12	0.53	82.40	Good
Learning engagement	4.47	0.39	89.40	Very Good
Overall	4.32	0.45	86.40	Very Good

The questionnaire results indicate that students perceived the inquiry-based learning design positively, with an overall mean score of 4.32 (SD = 0.45) corresponding to 86.40%, which was categorized as Very Good. The highest score was observed for learning engagement (M = 4.47), indicating that the inquiry activities successfully promoted students' participation and motivation throughout the learning process. In contrast, scientific argumentation received the lowest mean score (M = 4.12), suggesting that constructing evidence-based explanations remained relatively challenging for elementary students despite their active participation in inquiry activities.

Preliminary Evaluation of Students' Scientific Literacy

Students' scientific literacy was evaluated using a one-group pretest–posttest design involving thirty-two elementary school students. The assessment measured the three competency domains proposed in the OECD science framework: explaining scientific phenomena, evaluating and designing scientific inquiry, and interpreting scientific data and evidence.

Table 3. Descriptive Statistics of Students' Scientific Literacy Scores

Assessment	N	Minimum	Maximum	Mean	SD
Pretest	32	42	76	58.84	8.21
Posttest	32	70	96	84.31	6.54

The descriptive statistics demonstrate a substantial improvement in students' scientific literacy following the implementation of the inquiry-based learning design. The mean score increased from 58.84 in the pretest to 84.31 in the posttest, indicating an average improvement of 25.47 points.

To determine whether this improvement was statistically significant, a paired-samples t-test was performed.

Table 4. Paired-Samples t-Test of Scientific Literacy Scores

Comparison	Mean Difference	t	df	p
Pretest–Posttest	25.47	16.82	31	< .001

The paired-samples t-test revealed a statistically significant difference between pretest and posttest scores ($t(31) = 16.82$, $p < .001$), indicating that students demonstrated significantly higher scientific literacy after participating in the inquiry-based learning activities.

To examine the magnitude of learning improvement, normalized gain (N-gain) scores were calculated.

Table 5. N-gain of Scientific Literacy Competencies

Scientific Literacy Competency	N-gain	Category
Explaining scientific phenomena	0.70	High
Evaluating and designing inquiry	0.65	Moderate
Interpreting scientific evidence	0.72	High
Overall	0.69	Moderate–High

The N-gain analysis indicates that the inquiry-based learning design produced a moderate-to-high improvement in students' scientific literacy. The highest improvement was observed in interpreting scientific evidence, whereas evaluating and designing scientific inquiry showed relatively lower gains, suggesting that inquiry planning remained a more demanding competency for elementary students.

Summary of Results

Overall, the findings suggest that the inquiry-based science learning design demonstrated high content validity during expert evaluation, received very positive responses from students during implementation, and showed promising preliminary evidence of improving scientific literacy. The combination of expert validation, students' positive perceptions, and improvements in scientific literacy provides initial empirical support for the feasibility and educational potential of the developed instructional design. These findings form the basis for the subsequent discussion, which interprets the results in relation to inquiry-based learning theory, scientific literacy, and previous empirical research.

DISCUSSION

The present study sought to develop an inquiry-based science learning design that supports the development of scientific literacy among elementary school students through the Educational Design Research approach. The findings demonstrate that the developed instructional design achieved high expert validity, received positive responses from students during classroom implementation, and showed promising evidence of improving students' scientific literacy. Rather than merely confirming the effectiveness of inquiry-based learning, these findings suggest that the quality of instructional design plays a decisive role in determining how inquiry principles are translated into meaningful classroom experiences. Consequently, the contribution of this study extends beyond evaluating a pedagogical approach by emphasizing the importance of systematically organizing inquiry activities to facilitate scientific reasoning.

The high validity achieved during expert evaluation indicates that the instructional design was theoretically coherent and pedagogically appropriate for elementary science education. This finding is particularly important because Educational Design Research emphasizes that instructional innovations should emerge from an iterative process integrating theoretical knowledge with contextual educational needs (McKenney & Reeves, 2019). The expert validation therefore represents more than a procedural requirement; it demonstrates that the instructional design successfully aligned inquiry activities, learning objectives, and scientific literacy competencies within a coherent pedagogical framework. Such alignment is essential because fragmented instructional planning often results in inquiry activities that are engaging but insufficiently connected to the intended learning outcomes. The present findings therefore reinforce the argument that instructional coherence constitutes a fundamental characteristic of effective inquiry-oriented learning environments.

Students' positive responses further indicate that the developed instructional design created learning experiences that were perceived as engaging, meaningful, and supportive of scientific inquiry. This finding may be interpreted through the constructivist perspective, which proposes that conceptual understanding develops most effectively when learners actively construct knowledge through interaction with authentic learning experiences rather than passively receiving information from teachers (Council, 2012). Throughout the implementation, students were required to formulate questions, plan investigations, interpret empirical evidence, and communicate scientific explanations. These learning experiences encouraged active cognitive engagement while simultaneously providing opportunities to connect conceptual understanding with scientific practices. Consequently, students were not positioned as recipients of scientific information but as participants in the process of scientific knowledge construction.

An important finding emerging from this study concerns the relatively lower performance of scientific argumentation compared with other dimensions of scientific literacy. Although students generally responded positively to inquiry activities, constructing evidence-based arguments remained comparatively challenging. This finding is theoretically understandable because scientific argumentation requires learners to integrate conceptual understanding, logical reasoning, and empirical evidence into coherent explanations, a competency that develops progressively throughout schooling. Previous research similarly indicates that elementary students frequently experience difficulties in justifying scientific claims despite demonstrating satisfactory conceptual understanding (Eymur & Çetin, 2024; Van Hoe, 2024). Therefore, the relatively lower achievement observed in scientific argumentation should not necessarily be interpreted as a weakness of the instructional design but rather as evidence that argumentation requires sustained instructional support and repeated opportunities for practice.

The observed improvement in students' scientific literacy is consistent with previous studies demonstrating the educational value of inquiry-based learning. Inquiry-oriented instruction has consistently been associated with improvements in scientific literacy, science process skills, critical thinking, and conceptual understanding because it actively engages learners in authentic scientific practices (Eymur & Çetin, 2024; Harefa, 2023; Sager et al., 2025). Nevertheless, the present findings contribute a perspective that has received comparatively less attention in previous studies. Much of the existing literature has focused on determining whether inquiry-based learning improves scientific literacy, whereas relatively few studies have examined how instructional design structures inquiry experiences to achieve such outcomes. The present study suggests that learning outcomes are influenced not solely by the adoption of inquiry as a teaching approach but by the extent to which inquiry activities are systematically organized into coherent pedagogical sequences. This distinction is important because classroom implementation often fails not due to the inadequacy of inquiry as a pedagogical philosophy but because inquiry activities are implemented in fragmented or incomplete ways.

This interpretation is supported by Morris (2025), who argues that inquiry instruction in many classrooms remains dominated by isolated experimental activities while giving limited attention to scientific questioning, evidence evaluation, and argument construction. The instructional design developed in the present study attempted to address this limitation by explicitly integrating question formulation, investigation planning, evidence interpretation, scientific argumentation, and reflective evaluation within a continuous instructional sequence. Consequently, students experienced inquiry not simply as experimentation but as a complete process of scientific reasoning. This finding extends previous discussions by demonstrating that comprehensive inquiry implementation depends largely on instructional design rather than on the inclusion of laboratory activities alone.

From a theoretical perspective, this study contributes to the growing body of literature on inquiry-based science education by proposing instructional sequencing as a critical pedagogical mechanism underlying scientific literacy development. Existing research has established the effectiveness of inquiry-based learning; however, less attention has been devoted to explaining why inquiry produces positive learning outcomes in elementary classrooms. The present findings suggest that scientific literacy develops when inquiry stages are intentionally connected to specific scientific literacy competencies. In other words, instructional design functions as the mechanism through which inquiry practices are transformed into meaningful learning experiences that support scientific reasoning. This conceptual contribution complements existing inquiry literature by emphasizing the importance of pedagogical design alongside instructional strategy.

The findings also have practical implications for elementary science education. Teachers frequently encounter difficulties when implementing inquiry-based learning because available instructional materials often provide general inquiry activities without explicitly describing how each activity contributes to scientific literacy development. The instructional design developed in this study offers a structured learning sequence that connects inquiry activities with clearly defined scientific literacy competencies. Such an approach may assist teachers in organizing inquiry lessons more systematically while maintaining alignment with curriculum objectives and international assessment frameworks such as PISA. Consequently, the developed instructional design has the potential to function not only as a classroom resource but also as a professional reference for improving inquiry implementation in elementary science education.

Despite these promising findings, several limitations should be acknowledged. The classroom implementation involved a single elementary school, one teacher, and a relatively small number of students, thereby limiting the generalizability of the findings. Furthermore, the instructional design was evaluated through an initial implementation using a one-group pretest–posttest design, which does not permit strong causal inference regarding instructional effectiveness. The expert validation process also involved a single validator, suggesting that future studies should include multiple experts representing different areas of expertise to strengthen content validity. Future research is therefore encouraged to implement the instructional design across multiple schools, involve larger and more diverse participant groups, employ quasi-experimental or mixed-methods designs, and investigate how inquiry-based instructional design influences the long-term development of scientific literacy across different educational contexts.

Overall, the findings demonstrate that inquiry-based learning becomes substantially more effective when supported by a systematically developed instructional design that explicitly integrates scientific questioning, investigation planning, evidence interpretation, and scientific argumentation. Accordingly, the principal contribution of this study lies not merely in confirming the educational value of inquiry-based learning but in demonstrating that instructional design serves as the pedagogical mechanism connecting inquiry practices with the development of scientific literacy in elementary science education.

CONCLUSION

This study developed an inquiry-based science learning design to foster scientific literacy among elementary school students using the Educational Design Research (EDR) approach. The findings indicate that the developed instructional design demonstrated satisfactory pedagogical quality through expert validation, was positively received by students during classroom implementation, and showed promising potential for supporting the development of scientific literacy. These findings suggest that the effectiveness of inquiry-based learning is influenced not only by the adoption of inquiry as a pedagogical approach but also by the quality of instructional design that systematically organizes students' learning experiences. By explicitly integrating question formulation, investigation planning, evidence interpretation, scientific argumentation, and reflective evaluation into a coherent instructional sequence, the developed learning design provides a structured pathway through which students actively engage in scientific reasoning rather than merely acquiring scientific knowledge.

From a theoretical perspective, this study contributes to the growing body of research on inquiry-based science education by emphasizing instructional design as a pedagogical mechanism that connects inquiry practices with the development of scientific literacy. While previous studies have largely focused on examining the effectiveness of inquiry-based learning, the present study highlights that the sequencing and integration of inquiry activities are equally important in enabling students to develop the competencies of explaining scientific phenomena, evaluating and designing scientific inquiry, and interpreting scientific evidence as articulated in the OECD scientific literacy framework. Accordingly, this study extends existing knowledge by proposing that well-designed inquiry sequences provide a stronger conceptual foundation for fostering scientific literacy in elementary science education.

The study also offers practical implications for science teaching in elementary schools. The developed instructional design provides teachers with a structured framework for implementing inquiry-oriented learning that aligns curriculum objectives with international scientific literacy competencies. Consequently, the instructional design may serve as a practical reference for teachers, curriculum developers, and educational practitioners seeking to strengthen students' scientific literacy through meaningful inquiry experiences. Nevertheless, the findings should be interpreted within the limitations of the study, including the implementation in a single school, the relatively small number of participants, the use of one expert validator, and the preliminary one-group evaluation design. These limitations restrict the generalizability of the findings and indicate that broader empirical validation is still required.

Future research is recommended to validate the instructional design across multiple schools involving more diverse student populations and multiple expert validators. Subsequent studies should also employ more rigorous research designs, such as quasi-experimental or mixed-methods approaches, to examine the effectiveness of the instructional design in comparison with other instructional approaches. In addition, further investigation is needed to explore the long-term impact of inquiry-based instructional design on students' scientific literacy, scientific argumentation, and higher-order thinking skills across different educational contexts. Such studies will strengthen the empirical evidence supporting inquiry-based instructional design and contribute to the continued advancement of science education research and practice.

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