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Integrating Problem-Based Learning, Tri-N, and Deep Learning to Develop Critical Thinking in 3T Elementary Science Education

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ABSTRACT: Developing critical-thinking skills in disadvantaged and geographically constrained elementary schools remains challenging because conventional instruction often provides limited opportunities for inquiry, contextual learning, and higher-order cognitive engagement. This study examined the implementation and classroom-level outcomes of an integrated Problem-Based Learning (PBL), Tri-N (Niteni–Nirokke–Nambahi), and Deep Learning framework for developing fifth-grade students' critical-thinking skills in a 3T (frontier, outermost, and least-developed) elementary school in Kupang Regency, Indonesia. A classroom action research design was employed within a convergent mixed-methods framework involving 28 students across two four-week intervention cycles. Quantitative data were obtained through critical-thinking assessments and analyzed across baseline, Cycle I, and Cycle II, while qualitative evidence was derived from classroom observations, student work, interviews, and teacher reflections. Students' overall critical-thinking mean increased from 57.5 at baseline to 68.2 in Cycle I and 78.6 in Cycle II, while mastery achievement increased from 32.1% to 60.7% and 85.7%, respectively. The largest gains occurred in evaluation (24.2 points) and inference (23.2 points), the two weakest dimensions at baseline. These improvements were accompanied by greater environmental observation, explanatory questioning, integration of local cultural knowledge with scientific concepts, and confidence in developing locally relevant solutions. Implementation fidelity also increased from 78.5% to 92.3% following contextual refinements addressing time, resource, language, and grouping constraints. The findings suggest that the integrated PBL–Tri-N–Deep Learning framework can provide a context-responsive pathway for strengthening critical-thinking practices by combining authentic problem solving, culturally grounded inquiry, and meaningful conceptual learning. However, given the absence of a comparison group and the single-school setting, the findings should be interpreted as evidence of progressive classroom-level improvement rather than definitive causal effects. The study contributes to context-responsive science pedagogy by demonstrating how local environmental and cultural resources can function as substantive learning assets in resource-constrained 3T education.

Keywords: 3T education; culturally responsive pedagogy; critical thinking; Deep Learning; elementary school; Problem-Based Learning; science education; Tri-N.

ABSTRAK: *Pengembangan keterampilan berpikir kritis pada sekolah dasar yang berada di wilayah tertinggal dan memiliki keterbatasan geografis masih menjadi tantangan karena pembelajaran konvensional sering kali memberikan kesempatan yang terbatas untuk melakukan inkuiri, pembelajaran kontekstual, dan keterlibatan kognitif tingkat tinggi. Penelitian ini mengkaji implementasi dan hasil pembelajaran pada tingkat kelas dari kerangka terpadu* Problem-Based Learning *(PBL), Tri-N (*Niteni–Nirokke–Nambahi*), dan* Deep Learning *dalam mengembangkan keterampilan berpikir kritis siswa kelas V pada sebuah sekolah dasar 3T (terdepan, terluar, dan tertinggal) di Kabupaten Kupang, Indonesia. Penelitian menggunakan desain penelitian tindakan kelas dalam kerangka* convergent mixed-methods *yang melibatkan 28 siswa selama dua siklus intervensi, masing-masing berlangsung selama empat minggu. Data kuantitatif diperoleh melalui asesmen berpikir kritis dan dianalisis pada tahap awal (*baseline*), Siklus I, dan Siklus II, sedangkan bukti kualitatif diperoleh melalui observasi pembelajaran, hasil kerja siswa, wawancara, dan refleksi guru. Rata-rata keterampilan berpikir kritis siswa secara keseluruhan meningkat dari 57,5 pada tahap awal menjadi 68,2 pada Siklus I dan 78,6 pada Siklus II, sedangkan persentase ketuntasan meningkat dari 32,1%*

*menjadi 60,7% dan 85,7%. Peningkatan gerberas terjadi pada dimensi evaluasi (24,2 poin) dan inferensi (23,2 poin), yang merupakan dua dimensi terlemah pada tahap awal. Peningkatan tersebut disertai dengan meningkatnya kemampuan siswa dalam melakukan pengamatan lingkungan, mengajukan pertanyaan eksplanatif, mengintegrasikan pengetahuan budaya lokal dengan konsep-konsep ilmiah, serta meningkatkan kepercayaan diri dalam mengembangkan solusi yang relevan dengan konteks lokal. Keterlaksanaan pembelajaran juga meningkat dari 78,5% menjadi 92,3% setelah dilakukan penyempurnaan kontekstual untuk mengatasi kendala waktu, sumber daya, bahasa, dan pengelompokan siswa. Temuan penelitian menunjukkan bahwa kerangka terpadu PBL–Tri-N–*Deep Learning *dapat menjadi pendekatan yang responsif terhadap konteks dalam memperkuat praktik berpikir kritis melalui perpaduan pemecahan masalah autentik, inkuiri yang berakar pada budaya, dan pembelajaran konseptual yang bermakna. Namun, karena penelitian ini tidak menggunakan kelompok pembanding dan hanya dilaksanakan pada satu sekolah, temuan harus ditafsirkan sebagai bukti adanya peningkatan pembelajaran secara progresif pada tingkat kelas, bukan sebagai bukti definitif mengenai hubungan sebab-akibat. Penelitian ini berkontribusi terhadap pengembangan pedagogi sains yang responsif terhadap konteks dengan menunjukkan bahwa sumber daya lingkungan dan budaya lokal dapat berfungsi sebagai aset pembelajaran substantif dalam pendidikan 3T yang memiliki keterbatasan sumber daya.*

Kata kunci: *berpikir kritis;* Deep Learning*; pendidikan 3T; pendidikan sains; pedagogi responsif budaya;* Problem-Based Learning*; sekolah dasar; Tri-N.*

INTRODUCTION

Educational inequality remains a persistent global challenge, particularly in geographically isolated and socioeconomically disadvantaged communities where students have unequal access to quality learning opportunities, qualified teachers, instructional resources, and contextually relevant educational experiences. UNESCO and the OECD have consistently highlighted the vulnerability of learners in marginalized, rural, and remote communities, where geographical isolation and limited educational infrastructure can reinforce disparities in learning outcomes (OECD, 2021). In Indonesia, these challenges are particularly evident in the *Terdepan, Terluar, dan Tertinggal* (3T) regions—frontier, outermost, and disadvantaged areas—where educational provision is frequently constrained by geographical, infrastructural, and socioeconomic conditions. Thus, improving learning quality in 3T schools requires more than transferring pedagogical models developed in well-resourced settings; it requires approaches that are simultaneously evidence-based, context-sensitive, culturally meaningful, and feasible under resource constraints.

Science education provides an important lens through which this challenge can be examined. Beyond the acquisition of factual knowledge, contemporary science education increasingly emphasizes students' capacity to interpret evidence, analyze problems, evaluate alternative explanations, and make reasoned decisions. These competencies are closely associated with critical thinking, which is widely regarded as a fundamental 21st-century competence for navigating complex social, environmental, and technological challenges (Uslan, 2024). Nevertheless, students in disadvantaged and remote educational settings may have fewer opportunities to engage in inquiry-oriented and intellectually demanding learning. In Kupang Regency, East Nusa Tenggara, which includes areas characterized by 3T conditions, science learning outcomes remain a concern, particularly with regard to the development of students' higher-order thinking and critical-thinking capacities (Informasi, 2023). This situation raises an important pedagogical question: how can science instruction in resource-constrained contexts be designed to simultaneously promote active inquiry, critical thinking, conceptual understanding, and meaningful connections with students' lived experiences?

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One important explanation lies in the instructional practices and learning environments available to students. Science instruction in elementary schools in disadvantaged areas has often been characterized by teacher-centered practices, including extensive use of lectures and limited opportunities for students to investigate authentic problems (Ghaleb, 2024). Such practices may provide efficient transmission of information but offer relatively limited opportunities for students to formulate questions, examine evidence, construct explanations, and evaluate solutions. The problem is compounded when instructional materials and learning media are disconnected from students' social, cultural, and environmental realities. When scientific concepts are presented primarily through decontextualized examples, students may struggle to perceive the relevance of science to their everyday lives, potentially reducing both engagement and opportunities for meaningful conceptual development (Dyan Wulan Sari HS, 2024). Therefore, pedagogical innovation in 3T contexts should not simply increase the use of instructional technology or introduce sophisticated learning resources; it should create opportunities for students to think scientifically through problems that are recognizable and meaningful within their own environment.

Problem-Based Learning (PBL) offers a theoretically relevant foundation for addressing this challenge. By organizing learning around authentic or ill-structured problems, PBL shifts students from passive recipients of information toward active participants in inquiry, problem analysis, evidence evaluation, and solution development. These processes provide a potentially strong mechanism for developing critical-thinking skills (Indra Himayatul Asri, 2024). However, the effectiveness of PBL should not be assumed to be context-independent. A problem may be pedagogically authentic in one setting but unfamiliar or culturally distant in another. Consequently, the implementation of PBL in 3T schools requires careful consideration of how problems are selected, how students' prior experiences are incorporated, and how learning activities are connected to their local environment. This suggests that the central issue is not merely whether PBL is effective, but how PBL can be contextualized so that its problem-solving mechanism becomes meaningful for learners living in geographically and culturally distinctive communities**.**

Culturally responsive and place-based pedagogical perspectives provide an important basis for addressing this limitation. Previous research indicates that PBL can produce stronger learning outcomes when combined with approaches that recognize students' cultural backgrounds, local knowledge, and everyday experiences (Rahmawati, 2022; Adeliana et al., 2021). In this regard, Ki Hajar Dewantara's educational philosophy provides a potentially valuable conceptual foundation. His Tri-N learning concept—*Niteni, Nirokke,* and *Nambahi*—offers a progressive learning process beginning with careful observation (*Niteni*), followed by imitation or modeling (*Nirokke*), and culminating in modification, enrichment, or innovation (*Nambahi*). Rather than positioning students merely as receivers of established knowledge, Tri-N encourages learners to observe phenomena, learn from existing examples, and subsequently develop or improve ideas through their own thinking. Previous studies have demonstrated the relevance of Tri-N for contextual and local-wisdom-based learning (Ermawati et al., 2020; Azizah, 2023; Andayani, 2021). Its emphasis on observation, experience, modeling, and innovation also provides a conceptual bridge between local knowledge and scientific inquiry.

Nevertheless, contextual relevance alone may not be sufficient to ensure meaningful science learning. Students need not only to encounter familiar

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phenomena but also to develop sufficiently deep conceptual understanding to explain those phenomena scientifically. This concern becomes particularly important in 3T contexts, where limited instructional resources may encourage teachers to prioritize simplified content transmission over conceptual exploration. The emerging Deep Learning approach provides a complementary perspective by emphasizing meaningful understanding, connections among concepts, reflection, and the application of knowledge to authentic situations (Damanik, 2025; Wijaya et al., 2025). When combined with contextual learning, Deep Learning may enable students to move beyond merely recognizing local phenomena toward explaining, interpreting, and applying scientific concepts to those phenomena.

The theoretical complementarity among these approaches provides the rationale for their integration. PBL supplies the inquiry and problem-solving structure; Tri-N provides a culturally and environmentally grounded learning process; and Deep Learning provides the mechanism for developing deeper conceptual connections and meaningful application. In an integrated framework, students can begin by observing phenomena that are directly connected to their environment (*Niteni*), engage in modeling and investigation while working collaboratively to understand an authentic problem (*Nirokke*), and subsequently formulate, modify, or develop solutions based on scientific concepts (*Nambahi*). Deep Learning strengthens this process by encouraging students to connect observations and solutions with underlying scientific principles rather than treating learning as the completion of isolated classroom tasks. Such integration is particularly relevant to 3T education because it does not depend exclusively on sophisticated technological infrastructure; instead, it can mobilize the local environment, students' experiences, and readily accessible learning resources as pedagogical assets.

Despite the growing literature on PBL, culturally responsive learning, Tri-N, and Deep Learning, an important research gap remains. First, existing studies have predominantly examined these pedagogical approaches **independently**, making it difficult to determine how their mechanisms can operate synergistically within a single instructional framework. Second, research on PBL and critical thinking has frequently focused on general educational settings, with comparatively limited attention to the specific structural and resource constraints of 3T elementary schools. Third, although Tri-N offers a theoretically relevant indigenous pedagogical perspective, its integration with contemporary problem-based and deep-learning principles for science education remains insufficiently investigated. Fourth, there is limited empirical evidence concerning not only learning outcomes but also how such an integrated model is implemented in practice, what contextual barriers emerge, and how teachers and students negotiate those barriers in disadvantaged settings. These limitations indicate the need for research that moves beyond testing the isolated effectiveness of individual pedagogical models toward examining an integrated, contextually responsive instructional design.

This study addresses this gap by developing and examining a Tri-N and Deep Learning-integrated Problem-Based Learning (PBL) model for fifth-grade science education in a 3T context in Kupang Regency, East Nusa Tenggara, Indonesia. The proposed integration is theoretically significant because it connects three complementary dimensions of learning: problem solving and inquiry (PBL), cultural and contextual grounding (Tri-N), and conceptual depth and knowledge integration (Deep Learning). It is also practically significant because it seeks to demonstrate how pedagogical innovation can be designed for settings where educational resources are constrained and local environments constitute an

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important source of learning. Rather than viewing the 3T context solely as a deficit environment, this study conceptualizes local phenomena, experiences, and knowledge as potential pedagogical resources for strengthening science learning.

Accordingly, this study seeks to answer three questions: (1) How is the Tri-N and Deep Learning-integrated PBL model implemented in fifth-grade science learning in a 3T context? (2) To what extent does the integrated model improve students' critical-thinking skills? and (3) What contextual and pedagogical obstacles emerge during implementation, and what strategies can be formulated to address them? By addressing these questions, the study contributes empirical evidence to the literature on context-responsive science pedagogy and extends current discussions of PBL, indigenous/local-wisdom-based education, and Deep Learning. More broadly, the study seeks to demonstrate that improving educational quality in disadvantaged regions requires not merely the replication of mainstream instructional models, but the theoretical and pedagogical integration of evidence-based approaches with the cultural, environmental, and material realities of the learners they are intended to serve**.**

METHODS

Research Design

This study employed a Classroom Action Research (CAR) design within a convergent mixed-methods framework to examine the implementation and classroom-level outcomes of an integrated Problem-Based Learning (PBL), Tri-N, and Deep Learning approach for developing elementary students' critical-thinking skills in a disadvantaged and geographically constrained educational setting. The CAR design was selected because the study aimed not only to assess changes in students' learning outcomes but also to systematically identify implementation challenges and refine the instructional intervention through successive cycles of evidence-informed reflection.

The study followed the cyclical framework of Kemmis and McTaggart (1988), comprising four interconnected stages: planning, action, observation, and reflection. Two intervention cycles were conducted, with each cycle lasting four weeks. The iterative structure enabled the researchers to use evidence from the first cycle to modify instructional materials, teacher scaffolding, contextual learning activities, and implementation strategies in the second cycle.

A convergent mixed-methods design was incorporated to provide complementary evidence from quantitative and qualitative sources. Quantitative data were used to examine changes in students' critical-thinking performance, whereas qualitative data were used to examine how the integrated model was enacted, how students experienced the learning process, how teachers adapted the intervention, and what contextual factors facilitated or constrained implementation. The two strands of evidence were analyzed separately and subsequently integrated during interpretation (Creswell, 2012). The methodological logic of the study can be summarized as follows: Baseline assessment (T0) → Cycle I → Reflection and refinement → Cycle II → Final assessment (T2) → Mixed-methods integration.

The intervention was designed around the theoretical complementarity of the three pedagogical components. PBL provided the problem-solving and inquiry structure; Tri-N (*Niteni–Nirokke–Nambahi*) provided the contextual and experiential learning sequence; and Deep Learning supported conceptual depth, meaningful connections, reflection, and application. Thus, the three approaches

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were operationalized as an integrated instructional framework rather than implemented as independent teaching models.

Research Context and Setting

The study was conducted at Christian Elementary School Mater Carmeli, Kupang Regency, East Nusa Tenggara, Indonesia. The school was selected purposively because it represents an educational context characterized by geographical isolation, limited infrastructure, and restricted access to digital learning resources. The school is located approximately 45 km from the nearest urban center and experiences intermittent internet connectivity, generally limited to a 2G network.

The school had 156 students distributed across Grades 1–6 and eight teachers. These contextual characteristics were considered important because the intervention was intentionally designed to rely primarily on locally available environmental phenomena, teacher-guided inquiry, collaborative learning, and low-cost instructional resources rather than requiring continuous access to digital technology. The study context was treated as an integral component of the intervention rather than merely as a geographical location. Local environmental phenomena and students' everyday experiences were incorporated into science problems and learning activities to strengthen the relevance of scientific concepts to students' lived experiences.

Participants and Sampling

The primary participants were 28 fifth-grade students, consisting of 15 males and 13 females, with a mean age of 10.8 years (SD = 0.7). The participants represented the intact fifth-grade class in the selected school. Because the study was conducted as classroom action research within an authentic instructional setting, total population sampling of the intact class was employed; all students enrolled in the class participated in the instructional intervention. The students' linguistic and sociocultural backgrounds were considered during intervention design. All students used Bahasa Kupang in their daily communication, while 25 of the 28 students (89.3%) also reported using local Timorese dialects. Contextual examples and classroom discussions were therefore designed to accommodate students' everyday linguistic and environmental experiences. Three teachers served as secondary participants and key informants: the fifth-grade classroom teacher, a science coordinator, and the school principal. Their professional experience was 5, 6, and 8 years, respectively. These participants contributed qualitative information concerning instructional implementation, teacher adaptation, school-level support, resource limitations, and perceived changes in students' engagement and learning.

The study did not use a separate control group because its primary purpose was to investigate and iteratively improve classroom practice within an authentic educational setting. Consequently, observed changes are interpreted as classroom-level evidence of improvement associated with the intervention, rather than as definitive causal effects attributable exclusively to the intervention.

Intervention Framework

The integrated PBL–Tri-N–Deep Learning model was operationalized through a structured sequence of learning activities. PBL served as the overarching instructional architecture. Students were introduced to authentic or contextualized science problems, engaged in problem analysis and investigation, collaborated to evaluate information and evidence, formulated explanations, and

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developed possible solutions. Within this structure, the Tri-N sequence provided the contextual learning pathway: 1) Niteni – students carefully observed local phenomena, identified relevant features, and formulated initial questions; 2) Nirokke – students examined examples, models, demonstrations, or existing solutions and used them as references during investigation; and 3) Nambahi – students modified, extended, evaluated, or developed solutions based on their scientific understanding.

Deep Learning principles were embedded throughout these stages by requiring students to connect observations with scientific concepts, explain relationships among concepts, reflect on their learning, and apply knowledge to authentic situations. The integration can therefore be conceptualized as seen at Table 1.

Table 1. Integration of Problem-Based Learning, Tri-N, Deep Learning, and Critical-Thinking Processes

PBL Component	Tri-N Process	Deep Learning Emphasis	Critical-Thinking Process
Problem orientation	Niteni	Meaningful engagement with authentic phenomena	Interpretation
Problem investigation	Niteni–Nirokke	Conceptual connection and evidence use	Analysis
Development of explanations	Nirokke	Deep conceptual understanding	Inference
Evaluation of alternatives	Nirokke–Nambahi	Reflection and knowledge integration	Evaluation
Solution development and reflection	Nambahi	Application and transfer	Explanation

This operationalization was maintained across both cycles. However, the instructional materials, contextual examples, teacher scaffolding, and learning resources were revised following the reflection stage of Cycle I.

Research Procedure

The intervention consisted of two CAR cycles (Figure 1), each lasting four weeks. Each cycle followed the sequence of planning, action, observation, and reflection.

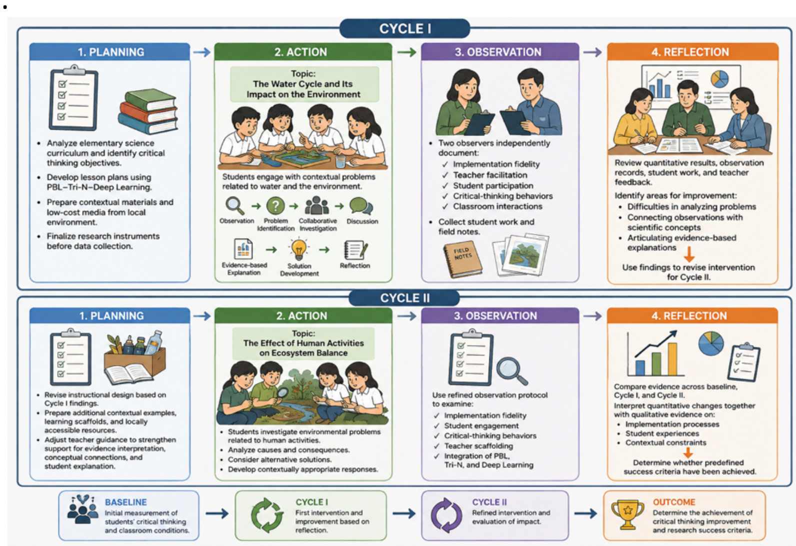

Figure 1. Two-cycle action research

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Data Collection and Measurement Points

To enable systematic assessment of change, critical-thinking performance was measured at three points: 1) T0 (baseline): before implementation of Cycle I; 2) T1: following completion of Cycle I; and 3) T2 (final): following completion of Cycle II. The same construct and comparable cognitive demands were maintained across the three assessments. Equivalent test forms were used where appropriate to minimize potential score inflation caused by repeated exposure to identical items. Classroom observations were conducted throughout both cycles. Semi-structured interviews were conducted with selected students and the participating teachers following classroom implementation, with additional interviews used when clarification of emerging findings was required.

Research Instruments

Critical-Thinking Skills Test

Students' critical-thinking skills were assessed using a researcher-developed instrument informed by Ennis's (2011) framework. The instrument consisted of 25 items representing five dimensions: interpretation, analysis, evaluation, inference, and explanation. Fifteen items were multiple-choice questions requiring students to provide reasoning for their selected responses, while ten were open-ended scenario-based questions requiring students to analyze contextual science problems and justify their conclusions. Content validity was examined by two experts in science education. The instrument obtained an Aiken's V coefficient of 0.87, indicating satisfactory content validity. Internal consistency analysis produced a Cronbach's alpha coefficient of 0.82. For open-ended responses, scoring criteria were established using an analytic rubric based on the five critical-thinking dimensions. The rubric differentiated levels of response according to the accuracy, relevance, reasoning, evidence use, and justification demonstrated by students.

Classroom Observation Instrument

A structured observation rubric was developed to assess the implementation fidelity of the integrated PBL–Tri-N–Deep Learning model. The instrument contained indicators covering three domains: PBL implementation, Tri-N enactment, and Deep Learning processes. The PBL indicators included problem orientation, investigation, collaboration, evidence use, and solution development. Tri-N indicators assessed observation of contextual phenomena, learning through examples or models, and modification or innovation of ideas. Deep Learning indicators assessed conceptual understanding, knowledge connections, reflection, and application. Each indicator was rated using a four-point scale: 1 = emerging, 2 = developing, 3 = proficient, and 4 = advanced. Two observers independently coded 30% of the observed sessions. Inter-rater reliability yielded Cohen's $\kappa = 0.84$, indicating substantial agreement.

Semi-Structured Interviews

Semi-structured interview protocols were developed for students and teachers. Student interviews explored learning experiences, perceptions of the Tri-N sequence, engagement with contextual problems, perceived changes in thinking, and connections between science concepts and everyday experiences. Teacher and principal interviews focused on implementation feasibility, teacher adaptation, student engagement, instructional resources, institutional support, and contextual barriers. The interview protocol was reviewed before

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implementation to ensure alignment with the research questions and conceptual framework.

Documentation

Documentation included lesson plans, teacher implementation notes, anonymized student work, researcher field notes, and photographs of classroom activities where appropriate consent had been obtained. These materials served as supplementary evidence for examining implementation processes and triangulating findings from tests, observations, and interviews.

Quantitative Data Analysis

Quantitative analysis was conducted using descriptive and inferential statistics. Mean scores, standard deviations, score changes, and the percentage of students achieving the minimum mastery criterion were calculated for each measurement point. Because the same students were assessed repeatedly at T0, T1, and T2, changes in critical-thinking scores were examined using repeated-measures ANOVA. The assumption of sphericity was evaluated using Mauchly's test. When the assumption was violated, the Greenhouse–Geisser correction was applied. Significant omnibus effects were followed by appropriate pairwise comparisons with adjustment for multiple testing.

Effect sizes were reported alongside statistical significance to assess the practical magnitude of observed changes. Cohen's d was calculated for relevant pairwise comparisons, while an appropriate repeated-measures effect-size estimate was reported for the overall within-subject effect. Given the classroom-level nature of the study and the absence of a control group, inferential results were interpreted cautiously. Statistical significance was not treated as evidence of definitive causal effectiveness. Instead, the statistical analysis was used to characterize the magnitude and consistency of changes occurring during the intervention.

The predefined classroom success criteria were: 1) at least 75% of students achieved the minimum mastery criterion (KKM ≥70); and 2) students demonstrated a meaningful improvement in critical-thinking performance, operationalized as at least a medium effect size ($d \geq 0.50$). Critical-thinking scores were also examined by dimension to determine whether improvement was distributed across interpretation, analysis, evaluation, inference, and explanation.

Qualitative Data Analysis

Qualitative data from observations, interviews, student work, documentation, and field notes were analyzed using reflexive thematic analysis following Braun and Clarke's framework. Analysis proceeded through six iterative phases: familiarization with the data, generation of initial codes, development of candidate themes, review of themes, definition and naming of themes, and production of the analytical narrative. Initial coding focused on the implementation of the three pedagogical components, students' critical-thinking behaviors, teacher scaffolding, contextual relevance, student engagement, conceptual understanding, language-related issues, resource constraints, and implementation challenges.

Qualitative analysis was conducted iteratively across the two cycles. Findings from Cycle I were used as formative evidence during the reflection stage and informed the modification of Cycle II. This process enabled the qualitative strand to function not only as an explanatory component but also as part of the pedagogical improvement process inherent in CAR.

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Mixed-Methods Integration

Integration occurred after the independent analysis of quantitative and qualitative data. The researchers used a convergence and complementarity approach to compare patterns across data sources. Quantitative data provided evidence regarding the direction and magnitude of changes in critical-thinking performance, while qualitative data provided explanations of the classroom processes associated with those changes. For instance, an increase in students' analysis scores was examined against observational evidence of students' increased engagement in problem identification, evidence examination, and causal reasoning. Similarly, dimensions showing limited improvement were examined in relation to qualitative evidence concerning instructional difficulties, insufficient scaffolding, language issues, or resource limitations.

The integrated interpretation therefore addressed three levels of evidence: Outcome evidence → Process evidence → Contextual explanation. This integration allowed the study to determine not only whether students' critical-thinking performance changed, but also how the integrated model was enacted and which contextual conditions influenced its implementation.

Trustworthiness and Methodological Rigor

Several procedures were implemented to strengthen the methodological rigor of the study. Quantitative instrument quality was supported through expert validation and internal-consistency testing. Observation data were independently coded by two observers, and inter-rater agreement was quantified using Cohen's kappa. For qualitative data, credibility was strengthened through methodological and source triangulation, involving observations, interviews, student work, documentation, and field notes. Evidence was compared across participants and across intervention cycles to identify convergence as well as discrepancies. An audit trail was maintained throughout the research process, including lesson plans, observation records, coding decisions, field notes, student work, and cycle-reflection records. The iterative reflection process also provided a mechanism for examining how evidence from Cycle I informed modifications implemented in Cycle II.

Ethical Considerations

Prior to data collection, permission to conduct the study was obtained from the school administration. Written informed consent was obtained from parents or legal guardians, and participating students received an age-appropriate explanation of the study procedures. Participation in research data collection was voluntary, and students' participation or non-participation did not affect their regular academic assessment. Student identities were protected through coded identifiers, and personally identifiable information was excluded from the research dataset and reporting. Photographic documentation was conducted only when appropriate consent had been obtained. Research data were stored securely, accessed only by the research team, and used exclusively for research purposes. The researchers also ensured that the intervention remained consistent with the regular curriculum and that participation did not deprive students of instructional time or educational opportunities.

RESULTS AND DISCUSSION

Results

Baseline Conditions and Initial Critical-Thinking Performance

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The baseline assessment established a relatively low level of critical-thinking performance among the 28 participating students. The overall mean score was 57.5 (SD = 7.8) on a 100-point scale, below the predetermined Minimum Mastery Criteria (KKM) of 70. Only 9 students (32.1%) achieved the mastery criterion, whereas 19 students (67.9%) remained below the expected threshold.

Substantial variation was observed across the four critical-thinking dimensions. Evaluation represented the weakest dimension, with a mean score of 51.7 (SD = 9.1), and 24 students (85.7%) scoring below the KKM. Inference produced a mean score of 54.2 (SD = 8.6), with 22 students (78.6%) below the criterion. Analysis showed comparatively stronger performance, although the mean remained below mastery at 58.3 (SD = 7.9), with 21 students (75.0%) below the KKM.

Table 2. Baseline Critical-Thinking Performance of Participants (N = 28)

Critical-Thinking Dimension	Mean (SD)	Score Range	Below KKM, n (%)
Analysis	58.3 (7.9)	42–73	21 (75.0%)
Evaluation	51.7 (9.1)	35–68	24 (85.7%)
Inference	54.2 (8.6)	38–71	22 (78.6%)
Overall Critical Thinking	**57.5 (7.8)**	**40–72**	**19 (67.9%)**

Note: KKM = Minimum Mastery Criteria; KKM was set at 70; maximum possible score = 100.

The assessment results were consistent with observations of classroom practice. Before the intervention, approximately 87% of observed instructional time was teacher-centered, while only 23% of observed interactions involved higher-order thinking activities. Students had relatively few opportunities to formulate questions, examine evidence, evaluate alternative explanations, or develop solutions independently. Local environmental and cultural knowledge was also minimally incorporated into science learning.

The baseline findings therefore indicated two interconnected conditions: students' critical-thinking performance was below the predetermined mastery level, and the prevailing instructional environment provided limited opportunities for sustained higher-order cognitive engagement. These conditions provided the empirical basis for implementing the integrated PBL–Tri-N–Deep Learning intervention.

Cycle I: Initial Intervention Effects and Implementation Constraints

Cycle I focused on the topic “The Water Cycle and Its Impact on the Environment”. The intervention engaged students in contextual problem situations involving water and environmental conditions. Learning activities incorporated observation, problem identification, collaborative investigation, discussion, evidence-based explanation, solution development, and reflection. The initial implementation achieved 78.5% protocol fidelity. Although most components of the instructional framework were implemented, observations revealed several operational constraints. Time-management difficulties occurred in 89% of observations, followed by resource-accessibility constraints (75%) and language code-switching difficulties (68%). These challenges were particularly apparent during investigation, discussion, and explanation phases, which required students to articulate reasoning and connect empirical observations with scientific concepts.

Despite these implementation constraints, students demonstrated substantial improvement in critical-thinking performance. The overall mean

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increased from 57.5 (SD = 7.8) at baseline to 68.2 (SD = 7.9) after Cycle I, representing a mean gain of 10.7 points. The paired-samples analysis indicated a statistically significant improvement, with a large standardized effect **(**Cohen's d = 1.36, p < .001**)**. The dimensional pattern also indicated improvement across all assessed domains. Analysis increased from 58.3 to 70.2, evaluation increased from 51.7 to 63.5, and inference increased from 54.2 to 65.4. The corresponding standardized effect sizes were large, ranging from d = 1.26 to d = 1.48.

Table 3. Critical-Thinking Performance from Baseline to Cycle I

Dimension	Baseline M (SD)	Cycle I M (SD)	Mean Gain	Cohen's d	p
Analysis	58.3 (7.9)	**70.2 (7.9)**	11.9	1.48	< .001
Evaluation	51.7 (9.1)	63.5 (8.9)	11.8	1.32	< .001
Inference	54.2 (8.6)	65.4 (9.2)	11.2	1.26	< .001
Overall Critical Thinking	**57.5 (7.8)**	**68.2 (7.9)**	**10.7**	**1.36**	**< .001**

Note: Paired-samples comparisons were conducted using df = 27. The Cycle I Analysis mean is reported as 70.2 to maintain consistency with the reported baseline mean and mean difference (11.9); the original value of 58.3 should be treated as a typographical error and verified against the raw dataset.

The proportion of students achieving the KKM increased from 9 students (32.1%) at baseline to 17 students (60.7%) following Cycle I, representing an improvement of 28.6 percentage points. Nevertheless, 11 students remained below the mastery criterion. This pattern suggested that the initial intervention was effective in generating improvement but was not yet sufficient to produce consistent mastery across the class.

Qualitative evidence helped explain this pattern. Three implementation challenges emerged from student interviews, observations, and field notes. Temporal-pedagogical tensions were identified by 82% of participants. Students and teachers reported that inquiry-oriented investigation required more time than conventional instruction. Cultural-academic integration challenges were reported by 64% of students, particularly when students attempted to translate familiar local knowledge into formal scientific explanations. In addition, collaborative learning difficulties were evident in 67% of observed group interactions, particularly regarding participation distribution and coordination of group tasks.

The Cycle I evidence therefore revealed an important distinction between initial cognitive gains and implementation readiness. Students appeared able to benefit from contextualized problem solving, but the instructional process required stronger scaffolding for evidence interpretation, conceptual connection, scientific explanation, and collaborative participation.

Cycle II: Instructional Refinement and Increased Implementation Fidelity

The findings from Cycle I were used to refine the intervention before Cycle II. Four modifications were introduced. First, the investigation sequence was reorganized to address temporal constraints. The core investigation phase was reduced from 40 to 25 minutes, while maintaining opportunities for observation and collaborative inquiry. Second, locally accessible resources were incorporated into approximately 85% of learning activities, reducing dependence on resources that were difficult to obtain. Third, explicit language scaffolding was introduced to support transitions between students' everyday language and scientific terminology. Fourth, differentiated grouping was implemented to provide

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additional support for students who required assistance in interpreting evidence and constructing explanations.

Cycle II addressed the topic "The Effect of Human Activities on Ecosystem Balance". Students investigated environmental problems associated with human activities, analyzed causes and consequences, considered alternative solutions, and developed responses that were feasible within their local context. Following these modifications, implementation fidelity increased from 78.5% in Cycle I to 92.3% in Cycle II. The improvement in fidelity indicates that the revised instructional sequence was more feasible under the existing classroom conditions and that the implementation barriers identified during the first cycle were substantially reduced. The reduction in implementation problems was accompanied by further improvement in students' critical-thinking performance. The overall mean increased from 68.2 (SD = 7.9) in Cycle I to 78.6 (SD = 7.1) in Cycle II, producing a further gain of 10.4 points. Relative to baseline, the total increase reached 21.1 points.

Table 4. Critical-Thinking Development Across the Two Intervention Cycles

Dimension	Baseline M (SD)	Cycle I M (SD)	Cycle II M (SD)	Total Gain	η^2
Analysis	58.3 (7.9)	70.2 (7.9)	79.7 (7.2)	21.4	.79
Evaluation	51.7 (9.1)	63.5 (8.9)	75.9 (8.3)	24.2	.72
Inference	54.2 (8.6)	65.4 (9.2)	77.4 (8.7)	23.2	.74
Overall Critical Thinking	**57.5 (7.8)**	**68.2 (7.9)**	**78.6 (7.1)**	**21.1**	**.81**

Note: η^2 represents the reported effect-size estimate associated with change across measurement occasions. The Analysis score for Cycle I has been harmonized with the reported mean difference in Table 2 and should be verified against the raw dataset.

The repeated-measures analysis demonstrated a significant effect of measurement time, $F(1.60, 43.16) = 58.90$, $p < .001$, $\eta^2 = .81$. The magnitude of the reported effect indicates a large change in critical-thinking performance across the intervention period. However, because the study employed a classroom action-research design without a non-intervention comparison group, the effect should be interpreted as change associated with the intervention over time rather than definitive causal attribution.

The largest total gain was observed in evaluation, which increased by 24.2 points from baseline to Cycle II. Inference increased by 23.2 points, while analysis increased by 21.4 points. These results indicate that the intervention was associated with improvement not only in students' ability to examine information but also in their capacity to judge evidence and construct reasoned conclusions. Most importantly from a classroom mastery perspective, the number of students achieving the KKM increased to 24 of 28 students (85.7%) by the end of Cycle II. Compared with the baseline achievement rate of 32.1%, this represented a 53.6-percentage-point increase.

Qualitative Evidence of Changes in Students' Critical-Thinking Practices

Quantitative improvements were complemented by qualitative evidence from interviews, classroom observations, student work, and teacher reflections. The thematic analysis identified three interconnected patterns: cultural-scientific integration, enhanced observation and questioning, and problem-solving confidence.

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Cultural-Scientific Integration

The first theme, identified by 64.3% of students, concerned the increasing ability to connect local cultural knowledge with formal scientific concepts. Students described the Tri-N component as providing a bridge between familiar experiences and scientific explanations. One student explained: "Niteni helped me see that our traditional ways of predicting rain actually connect to the water cycle." (Student 14). This account illustrates a shift from treating local knowledge as separate from formal science toward interpreting familiar practices through scientific concepts. The finding is particularly relevant to the contextual dimension of the intervention because students were not simply exposed to local examples; they were encouraged to examine, interpret, and connect those examples with disciplinary knowledge.

Enhanced Observation and Question Formulation

The second theme, reported by 89.3% of students, involved increased environmental awareness and more frequent formulation of explanatory questions. Students increasingly moved from describing observable phenomena toward asking questions concerning causes, processes, and consequences. One student stated: "I ask 'why' and 'how' questions about everything now." (Student 11). Classroom observations and student work were consistent with this perception. Students demonstrated greater willingness to inspect environmental phenomena, identify anomalies, and formulate questions requiring explanation. This pattern suggests that the intervention supported a transition from predominantly receptive participation toward more inquiry-oriented cognitive engagement.

Problem-Solving Confidence and Contextual Transfer

The third theme, identified by 60.7% of students, concerned students' growing confidence in developing solutions to environmental problems. Students increasingly applied classroom concepts to situations encountered in their homes and communities. For example, one student reported: "We found ways to prevent erosion using plants that grow here." (Student 5). This evidence indicates that students were beginning to transfer scientific understanding beyond the immediate classroom task. Rather than reproducing predefined answers, students generated responses based on locally available resources and environmental conditions. Such transfer provides qualitative evidence of the application-oriented dimension of critical thinking.

Changes in Implementation Constraints

The comparison between cycles showed a substantial reduction in the implementation constraints identified during Cycle I. Time-management problems decreased by approximately 60%, resource constraints decreased by 73%, and language-related barriers decreased by 76% during Cycle II. These changes coincided with the increase in implementation fidelity from 78.5% to 92.3%**.** The convergence of these findings indicates that the second cycle was not simply a repetition of the first intervention but represented a meaningful instructional refinement based on evidence generated during implementation.

Table 5. Changes in Implementation Fidelity and Key Constraints

Implementation Indicator	Cycle I	Cycle II	Change

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Protocol fidelity	78.5%	92.3%	+13.8 percentage points
Time-management problems	89%	35.6%*	−60%
Resource constraints	75%	20.3%*	−73%
Language barriers	68%	16.3%*	−76%

Note: Cycle II percentages are reconstructed from the reported percentage reductions and should be replaced by observed frequencies/percentages from the original observation dataset before final submission.

Teacher interviews provided additional evidence of implementation development. Teachers reported improvements in pedagogical content knowledge, culturally responsive teaching, student-centered facilitation, and assessment practices. Teachers also described greater awareness of the need to scaffold evidence interpretation and scientific explanation rather than relying primarily on direct transmission of content.

Convergence of Quantitative and Qualitative Findings

The quantitative and qualitative findings demonstrated a consistent pattern across the intervention. The baseline data showed low critical-thinking performance alongside predominantly teacher-centered instructional practices. Cycle I produced substantial improvements, but students and teachers continued to experience difficulties related to time, resources, language, collaboration, and conceptual explanation. These findings informed specific modifications to the instructional design. Following the Cycle II refinements, implementation fidelity increased to **92.3%**, while the overall critical-thinking score increased from **57.5 at** baseline to 78.6 at Cycle II. Mastery achievement similarly increased from **32.1% to 85.7%**. The qualitative evidence provided process-level explanations for these changes: students increasingly connected local knowledge with scientific concepts, asked more explanatory questions, interpreted environmental phenomena more actively, and developed locally relevant solutions. The convergence of the two forms of evidence is summarized in Table 6.

Table 6. Integrated Quantitative and Qualitative Evidence Across the Intervention

Phase	Quantitative Evidence	Qualitative Evidence	Interpretation
Baseline	Overall M = 57.5; 32.1% achieved KKM	Teacher-centered instruction; limited higher-order engagement; minimal local contextualization	Critical-thinking development was constrained by both student performance and instructional conditions
Cycle I	M increased to 68.2; 60.7% achieved KKM; d = 1.36	Students engaged more actively but experienced time, resource, language, and collaboration difficulties	Initial intervention generated substantial gains but required contextual refinement
Cycle II	M increased to 78.6; 85.7% achieved KKM; η^2 = .81	Greater observation, questioning, cultural-scientific connections, and problem-solving confidence	Refined implementation was associated with stronger and more consistent critical-thinking performance

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Overall	+21.1-point gain from baseline to Cycle II	Improved student participation and teacher facilitation	Quantitative improvement was accompanied by observable changes in learning processes

Overall, the results indicate that the PBL–Tri-N–Deep Learning framework was associated with substantial improvement in elementary students' critical-thinking performance across two iterative intervention cycles. The evidence further indicates that the effectiveness of the approach depended on contextual adaptation. The strongest outcomes emerged after instructional time, learning resources, language support, and grouping arrangements had been systematically modified in response to evidence from Cycle I.

Rather than indicating that the intervention alone caused the observed changes, the findings demonstrate that iterative instructional refinement was accompanied by increased implementation fidelity and progressively higher critical-thinking performance. This pattern is particularly relevant to classroom-based innovation because it demonstrates how an integrated pedagogical framework can be adapted to local classroom conditions while maintaining its core problem-based, culturally responsive, and cognitively demanding components.

Discussion

Interpreting the Development of Students' Critical Thinking

This study examined how an integrated PBL–Tri-N–Deep Learning framework was associated with the development of critical thinking among elementary school students through two iterative classroom action-research cycles. The findings demonstrate a consistent upward trajectory in students' critical-thinking performance, from an overall mean of 57.5 at baseline to 68.2 after Cycle I and 78.6 after Cycle II. The proportion of students achieving the predetermined mastery criterion increased from 32.1% to 60.7% and subsequently to 85.7%. These quantitative changes were accompanied by qualitative evidence of greater observation, question formulation, cultural-scientific integration, and confidence in developing locally relevant solutions.

The findings should be interpreted primarily as evidence of progressive change associated with an iterative pedagogical intervention, rather than as definitive evidence of causal effects. This distinction is important because the classroom action-research design did not include a non-intervention comparison group. Nevertheless, the convergence between quantitative improvement, increased implementation fidelity, classroom observations, student accounts, and teacher reflections strengthens the interpretation that the intervention contributed meaningfully to changes in students' learning processes.

The baseline findings provide an important explanation for the magnitude of the subsequent improvement. Students initially demonstrated particular weaknesses in evaluation and inference, while classroom observations indicated that instructional time was predominantly teacher-centered and provided relatively limited opportunities for higher-order thinking. This condition is consistent with the broader argument that critical thinking does not develop simply through exposure to disciplinary content; students need repeated opportunities to interpret information, examine evidence, question assumptions, justify claims, and apply knowledge to problems. In this respect, the intervention changed not only the content students encountered but also the cognitive architecture of classroom participation.

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The transition from teacher-directed learning toward problem-based, inquiry-oriented learning therefore represents a potentially important mechanism underlying the observed improvement. Instead of receiving scientific explanations primarily from the teacher, students were required to encounter a problem, investigate observable phenomena, discuss evidence, formulate explanations, and consider possible solutions. Such processes create repeated occasions for the cognitive operations represented in the assessment dimensions—analysis, evaluation, and inference.

Why the Integrated PBL–Tri-N–Deep Learning Framework May Have Supported Critical Thinking

The results suggest that the contribution of the framework lies less in any single pedagogical component than in the complementarity among PBL, Tri-N, and Deep Learning. Problem-based learning provided the structural mechanism for engaging students with meaningful problems. Rather than beginning with abstract scientific concepts, learning began with environmental phenomena that students could observe and discuss. This is important because authentic problems can create a cognitive need for students to seek explanations and evaluate possible solutions. The problem context consequently provided a meaningful reason for students to engage in analysis and inference rather than treating these processes as isolated assessment skills.

The Tri-N component added a culturally responsive dimension to this process. Students were encouraged to connect their existing experiences and local knowledge with scientific concepts. The qualitative finding that 64.3% of students recognized connections between traditional knowledge and formal science indicates that cultural contextualization was not merely an affective or motivational strategy. It potentially functioned as a cognitive bridge between students' prior knowledge and disciplinary reasoning.

This mechanism is illustrated by Student 14's statement that traditional ways of predicting rain could be connected with the scientific explanation of the water cycle. The significance of this finding lies in the movement from recognition to conceptual reconstruction. Students did not simply recall traditional knowledge; they attempted to reinterpret familiar practices through scientific concepts. Such movement can support deeper conceptual engagement because students are required to compare existing understandings with formal explanations.

The Deep Learning component further strengthened this process by emphasizing meaningful understanding, conceptual connections, reflection, and application rather than surface-level reproduction of information. The qualitative evidence of increased "why" and "how" questioning is particularly relevant in this regard. Students appeared increasingly oriented toward explanations and relationships rather than simply identifying observable facts.

The three components can therefore be understood as serving complementary functions: 1) PBL created the problem context and cognitive demand; 2) Tri-N connected scientific inquiry with students' cultural and experiential knowledge; and 3) Deep Learning supported conceptual integration, reflection, and transfer. The resulting instructional configuration may explain why the intervention was associated with improvements across multiple dimensions of critical thinking rather than improvement in a single skill.

The Strongest Development in Evaluation and Inference

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An important finding was that evaluation and inference, which were the weakest baseline dimensions, demonstrated substantial overall gains by Cycle II. Evaluation increased by 24.2 points and inference by 23.2 points from baseline to Cycle II. This pattern is educationally meaningful because these skills require students to move beyond identifying or describing information toward judging evidence and constructing defensible conclusions.

The improvement may be related to the increasing emphasis on evidence-based explanation during the intervention. Students were repeatedly required to observe phenomena, identify possible causes, compare explanations, and provide reasons for proposed solutions. Such activities create an authentic context in which evaluation and inference become necessary for completing the task rather than being presented as decontextualized cognitive exercises.

The findings also suggest that the intervention may have helped students move through a progression from observation → questioning → evidence interpretation → explanation → solution development. This sequence is particularly important in elementary science because younger learners may find abstract definitions of critical thinking difficult to internalize. When critical-thinking processes are embedded in concrete environmental problems, students can experience them as part of the process of solving a meaningful problem. However, the relatively lower Cycle II score for evaluation compared with analysis suggests that judging evidence may remain more cognitively demanding than identifying and organizing information. This finding has implications for future implementation. Teachers may need to provide more explicit scaffolding for distinguishing evidence from opinion, assessing the relevance of evidence, comparing competing explanations, and justifying why one explanation is more convincing than another.

Cultural Context as a Mechanism for Meaningful Science Learning

One of the distinctive contributions of the study is the incorporation of local cultural knowledge into a critical-thinking intervention. The findings indicate that students were more capable of relating traditional knowledge to scientific concepts when the instructional process explicitly created opportunities for such connections.

This finding challenges a narrow conception of contextual learning in which local examples are used only as illustrations of predetermined scientific concepts. In the present intervention, local knowledge became part of the epistemic starting point for inquiry. Students' experiences of weather, water, plants, erosion, and environmental change provided phenomena that could be questioned, investigated, and interpreted scientifically.

The qualitative evidence therefore suggests that culturally responsive science instruction can potentially serve two purposes simultaneously: strengthening the relevance of learning and creating opportunities for conceptual comparison. When students ask whether an observation from their community is consistent with a scientific explanation, they are implicitly engaging in comparison, evaluation, and inference.

This mechanism may be particularly important in contexts where students possess substantial environmental knowledge from everyday experience but have limited opportunities to connect that knowledge to formal school science. Rather than positioning local knowledge and scientific knowledge as competing systems, the intervention created opportunities for dialogue between them.

At the same time, the Cycle I findings concerning cultural-academic integration indicate that such integration is not automatic. Approximately 64% of

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students experienced difficulties in connecting cultural knowledge with academic science. This suggests that culturally responsive pedagogy requires careful teacher mediation. Without explicit conceptual scaffolding, local knowledge may remain at the level of anecdotal experience rather than becoming a resource for scientific reasoning.

From Observation to Questioning and Problem Solving

The strongest qualitative pattern concerned enhanced observation and question formulation, reported by 89.3% of students. This result is significant because observation is often treated as a basic science-learning activity, whereas the findings indicate its potential role as an entry point into higher-order thinking. The shift reported by students—from simply noticing environmental phenomena toward asking "why" and "how"—suggests a qualitative transformation in the nature of classroom participation. Students were increasingly positioned as investigators rather than passive recipients of information. This finding complements the quantitative improvement in critical-thinking scores and provides process-level evidence for how such improvement may have developed.

The problem-solving theme provides a further indication of transfer. Sixty percent of students reported greater confidence in generating solutions, including solutions based on locally available resources. For example, the proposal to use locally available plants to reduce erosion demonstrates movement from scientific understanding toward practical application. This pattern is consistent with the logic of problem-based learning, in which learning is organized around the need to understand and respond to authentic problems. However, the present findings extend this logic by showing that locality can provide both the problem and the resource base for the solution. Students were not required to reproduce externally prescribed solutions; instead, they considered responses that were feasible within their immediate environment.

Why Cycle II Produced Stronger Outcomes than Cycle I

The difference between the two cycles is particularly important for understanding the intervention. Cycle I generated substantial improvement but achieved only 78.5% implementation fidelity, while Cycle II reached 92.3% fidelity after specific modifications were introduced. This pattern indicates that pedagogical innovation cannot be separated from implementation conditions. The first cycle functioned not simply as an intervention phase but also as a diagnostic stage for identifying contextual barriers. Time-management problems, resource constraints, language difficulties, and collaborative-learning issues were transformed into design information for Cycle II.

The reduction of the investigation period from 40 to 25 minutes illustrates this adaptive process. Rather than removing inquiry activities because they required too much time, the researchers reorganized the sequence to make inquiry more feasible. Similarly, the use of locally accessible resources addressed resource constraints without abandoning the contextual orientation of the intervention. Language scaffolding was another critical adaptation. Because students were required to move between everyday expressions and scientific terminology, language became part of the cognitive challenge. Strengthening language support therefore did more than improve communication; it potentially enabled students to make their reasoning more explicit.

Differentiated grouping also addressed the social dimension of collaborative inquiry. The Cycle I finding that 67% of group interactions presented collaborative difficulties indicates that simply placing students in groups does not

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guarantee productive collaboration. Structured grouping and differentiated support were consequently necessary to transform group work into a mechanism for shared reasoning. The higher implementation fidelity in Cycle II, combined with further gains in critical thinking, supports the interpretation that instructional refinement was an important component of the intervention process. The study therefore contributes not only evidence concerning student outcomes but also evidence about how an integrated pedagogical model can be adapted through iterative classroom-based inquiry.

Implications for Teachers and Science Education

The findings have several implications for elementary science teaching. First, critical-thinking development should be embedded within disciplinary and contextual learning, rather than treated as an additional instructional objective. The present intervention integrated critical thinking into authentic science problems, allowing students to practice analysis, evaluation, and inference while learning scientific content. Second, local knowledge can be used as a pedagogical resource when it is accompanied by explicit scientific mediation. Teachers should not simply ask students to share traditional knowledge; they should guide students to examine observations, identify similarities and differences with scientific explanations, evaluate evidence, and construct conceptually defensible conclusions. Third, inquiry-oriented learning requires careful instructional time management. The Cycle I experience demonstrates that theoretically desirable learning activities can become ineffective if the sequence exceeds available classroom time. Teachers should therefore identify essential inquiry phases and allocate time strategically. Fourth, language scaffolding deserves greater attention in science education. Students may understand a phenomenon but still struggle to express an evidence-based explanation. Teachers should therefore provide sentence structures, scientific vocabulary, visual representations, and guided questioning to support the transition from informal descriptions to scientific reasoning. Finally, collaborative learning should be deliberately structured. Group formation alone is insufficient. Roles, accountability, differentiated tasks, and teacher monitoring may be required to ensure that collaboration generates genuine cognitive engagement.

Theoretical and Practical Contribution

The study contributes to the literature by positioning PBL, culturally responsive learning through Tri-N, and Deep Learning as complementary rather than isolated pedagogical strategies. The results suggest a possible conceptual pathway in which contextual problems activate inquiry, cultural knowledge provides meaningful prior knowledge, and deep-learning processes facilitate conceptual integration and reflection.

The proposed pathway can be represented as: Contextual Problem → Observation → Question Formulation → Cultural–Scientific Connection → Evidence Interpretation → Evaluation → Inference → Solution Development → Reflection and Transfer. This pathway provides a potential explanatory model for the observed development of critical thinking. Importantly, the findings suggest that the effectiveness of such integration depends on implementation quality. The increase in fidelity from 78.5% to 92.3% demonstrates that pedagogical integration requires adaptation to classroom time, available resources, language practices, and student collaboration.

The practical contribution is therefore twofold. At the student level, the intervention was associated with substantial improvement in critical-thinking

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performance and mastery achievement. At the teacher level, the intervention supported changes in pedagogical content knowledge, culturally responsive practices, student-centered facilitation, and assessment approaches. The model consequently has potential relevance for professional development programs that seek to integrate critical thinking with contextualized science education.

Limitations and Directions for Future Research

Several limitations should be considered when interpreting the findings. First, the study involved a relatively small sample of 28 students within a single classroom context. The findings therefore cannot be generalized directly to other schools, regions, or educational systems without further empirical validation. Second, the classroom action-research design did not include a control or comparison group. The observed improvement may therefore reflect multiple influences, including maturation, repeated exposure to assessment procedures, increased familiarity with classroom tasks, or other contextual factors. Future studies should employ quasi-experimental or cluster-randomized designs where feasible to examine the relative contribution of the integrated framework more rigorously. Third, the intervention involved multiple pedagogical components simultaneously. Consequently, the present study cannot determine whether PBL, Tri-N, or Deep Learning individually produced the greatest contribution to the observed changes. Future research could employ factorial, comparative, or sequential designs to examine the relative and interaction effects of these components. Fourth, some implementation indicators were derived from observational judgments and participant reports. Although the use of two observers and multiple qualitative sources strengthened credibility, future research could further improve measurement reliability through inter-rater reliability coefficients, standardized observation instruments, and independent coding procedures. Finally, the present study focused on relatively short-term changes across two intervention cycles. Future longitudinal research should examine whether the observed gains in critical thinking are sustained over time and whether students transfer these skills to new scientific topics, academic disciplines, and everyday decision-making contexts.

CONCLUSION

This study examined the implementation and classroom-level outcomes of an integrated Problem-Based Learning (PBL), Tri-N, and Deep Learning framework for developing critical-thinking skills in fifth-grade science learning in a 3T elementary school context in Kupang Regency, Indonesia. The findings demonstrate a consistent pattern of improvement across two iterative classroom action-research cycles. Students' mean critical-thinking score increased from 57.5 at baseline to 68.2 after Cycle I and 78.6 after Cycle II, representing a total gain of 21.1 points. The proportion of students achieving the predetermined mastery criterion also increased substantially, from 32.1% to 60.7% and ultimately to 85.7%.

The qualitative findings provide complementary evidence that the observed improvement was accompanied by meaningful changes in students' learning processes. Students demonstrated greater engagement in environmental observation, question formulation, evidence interpretation, cultural–scientific connection, and the development of locally relevant solutions. Particularly notable was the improvement in evaluation and inference, which were initially the weakest dimensions of critical thinking but recorded the largest gains by the end of Cycle II. These findings suggest that embedding critical-thinking processes

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within authentic environmental problems may provide elementary students with concrete opportunities to analyze evidence, evaluate alternatives, construct explanations, and develop reasoned solutions.

The study further demonstrates that the contribution of the integrated framework lies in the complementarity of its three pedagogical components. PBL provided the inquiry and problem-solving structure, Tri-N connected scientific learning with students' cultural knowledge and lived experiences, and Deep Learning supported meaningful conceptual connections, reflection, and application. The increase in implementation fidelity from 78.5% in Cycle I to 92.3% in Cycle II, following targeted adaptations in instructional time, locally available resources, language scaffolding, and collaborative grouping, indicates that contextual adaptation was an important condition for successful implementation.

Importantly, the findings should be interpreted as evidence of progressive classroom-level improvement associated with the intervention rather than as definitive evidence of causal effectiveness. The absence of a control or comparison group and the small sample from a single classroom limit the generalizability and causal interpretation of the findings. Nevertheless, the convergence of quantitative outcomes, classroom observations, student experiences, student work, and teacher reflections strengthens the evidence that the integrated framework supported meaningful changes in students' critical-thinking practices.

The study contributes a context-responsive pedagogical pathway for science education in resource-constrained 3T settings: contextual problem → observation → question formulation → cultural–scientific connection → evidence interpretation → evaluation → inference → solution development → reflection and transfer. The findings indicate that educational innovation in disadvantaged contexts does not necessarily require sophisticated technological infrastructure; rather, meaningful learning can be strengthened by integrating evidence-based pedagogy with local environments, cultural knowledge, accessible resources, and deliberate teacher scaffolding. Future research should validate the framework across multiple schools and contexts using comparative or quasi-experimental designs and examine whether the observed critical-thinking gains are sustained and transferable over time.

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