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DEVELOPING A CULTURALLY RESPONSIVE PROJECT-BASED LEARNING MODEL INTEGRATING SIMALUNGUN MARHAROAN BOLON TO FOSTER STUDENTS' CRITICAL THINKING SKILLS

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ABSTRACT

The integration of local wisdom into science education is increasingly recognised as essential for strengthening scientific culture and promoting culturally responsive learning. This study aimed to develop and validate a culturally responsive Project-Based Learning (PJBL) model integrating the Simalungun Marharoan Bolon philosophy to foster students' critical thinking skills. Employing a design-based research approach followed by a quasi-experimental validation phase, the study involved 64 secondary school students, divided into an experimental ($n = 32$) and a control ($n = 32$) group. The development process included needs analysis, model design, expert validation, limited trials, and field testing. Content validity analysis showed high model validity (Aiken's $V = 0.89$), and reliability testing indicated strong internal consistency (Cronbach's $\alpha = 0.91$). Effectiveness testing revealed a statistically significant improvement in students' critical thinking skills in the experimental group (pretest $M = 61.47$, $SD = 7.82$; posttest $M = 82.63$, $SD = 6.95$), $t(31) = 12.54$, $p < .001$, with a large effect size (Cohen's $d = 2.22$). In contrast, the control group demonstrated a moderate improvement (Cohen's $d = 0.68$). ANCOVA results, controlling for pretest scores, indicated a significant effect of the intervention on posttest critical thinking scores, $F(1, 61) = 46.87$, $p < .001$, $\eta^2 = .43$, suggesting a strong practical impact. These findings demonstrate that embedding Marharoan Bolon values, emphasising collective responsibility and collaborative inquiry, within PJBL significantly enhances students' higher-order thinking. The study contributes to the discourse of scientific culture by demonstrating how indigenous knowledge systems can meaningfully reconstruct contemporary science pedagogy.

KEYWORDS: Culturally Responsive Pedagogy; Project-Based Learning; Marharoan Bolon; Critical Thinking; Local Wisdom.

1. INTRODUCTION

Education in the twenty-first century is increasingly expected to develop higher-order competencies, particularly critical thinking, problem solving, creativity, and collaboration, rather than focusing only on the acquisition of subject content (Arisa & Sitinjak, 2022). Reviews of STEM/STEAM-oriented education consistently associate these goals with active, constructivist learning designs, in which students engage in inquiry, produce artefacts, and collaborate to address authentic problems (Yazici, 2020). In science education specifically, the emphasis on higher-order thinking is frequently operationalised through students' participation in scientific practices (e.g., observing, hypothesising, collecting and analysing data, and making inferences), which are widely understood as foundations for building evidence-based reasoning and, in turn, critical thinking capacity(Prahanı et al., 2023). Accordingly, instructional approaches that foreground sustained inquiry and collaborative problem-solving have become prominent in the contemporary research literature and curriculum discussions (Hanif et al., 2024).

Within the science-education literature represented in the available sources, "scientific culture" can be approached pragmatically as learners' participation in scientific practices and dispositions that emphasise evidence-based inference, analytical reflection, and collaborative discourse (Shahat et al., 2024). Science process skills, such as observation, hypothesis formation, data collection, analysis, and drawing conclusions grounded in empirical evidence, are repeatedly linked to the development of students' logic, problem-solving, and critical thinking (Jabbar & Halim, 2024). This linkage is important because it frames critical thinking in science not merely as generic reasoning, but as reasoning constrained by evidence and methodological rigour, which is cultivated through repeated practice in inquiry-oriented learning tasks (Novianto, 2023).

Project-Based learning is widely characterised as an instructional approach organised around authentic projects that require learners to engage in inquiry, exercise autonomy, and produce realistic artefacts or performances (DongJin & Ashari, 2024). Conceptual discussions of PjBL emphasise project "centrality" to the curriculum and the importance of driving questions, constructive investigation, autonomy, and realism, conditions theorised to promote meaningful learning and higher-order thinking (Farid et al., 2021). In addition, PjBL is repeatedly framed as a constructivist and social-constructivist methodology in which knowledge is built through collaborative activity and applied to real problems, thereby supporting transferable learning outcomes beyond rote content mastery (Mulyani & Arif, 2021). Because PjBL structures students' work as collective inquiry and problem solving, it is also commonly linked to the development of collaboration and communication alongside cognitive outcomes (Morini et al., 2024).

While PjBL research strongly supports inquiry-based and collaborative designs for higher-order learning, the provided sources also point to a complementary line of work emphasising the reconstruction of "original" or community-based knowledge into scientific understanding, often discussed under the umbrella of ethnoscience-based learning (Mulyadi et al., 2023). Ethnoscience-oriented instruction is described as requiring a shift from teacher-centred to student-centred learning and from individual to collaborative learning, with the explicit aim of transforming community knowledge into scientifically structured knowledge to strengthen students' critical thinking. This framing is consistent with broader claims in the sources that limited opportunities for participation, learning experiences, and argumentation can constrain the development of critical thinking in science, implying that culturally grounded and participatory designs may address persistent instructional limitations.

Building on the documented alignment between PjBL and collaborative inquiry, this study proposes grounding PjBL design in a specific local wisdom construct, Marharoan Bolon, as an explicit cultural anchor for collaborative work norms and shared responsibility within project activities. This rationale is consistent with the broader PjBL literature, which repeatedly treats group success, cooperative learning, and collaborative discourse as integral to effective projects and to the development of higher-order skills (Widiawati et al., 2023). It is also consistent with constructivist PjBL frameworks that foreground social interaction and collaborative thinking as mechanisms for knowledge construction and transfer to real-world problem-solving (DongJin & Ashari, 2024).

The available literature indicates three robust trends: (i) PjBL is extensively discussed and empirically studied as a constructivist approach linked to critical thinking and other twenty-first-century skills (Prihatin & Gunawan, 2024); (ii) STEM/STEAM and design-based integrations often use PjBL as an organising pedagogy to promote critical thinking, problem solving, and collaboration through experiential learning (Novianto, 2023); and (iii) ethnoscience-based learning, including ethnoscience-based PjBL, has been investigated as a culturally contextualised pathway for strengthening critical thinking, with meta-analytic evidence suggesting positive effects,. Nevertheless, systematic review work in PjBL also notes continuing needs for more extensive and systematic evaluation and clearer guidance on how to effectively design and implement PjBL in specific contexts, indicating that "design-and-validation" questions remain open (Subiyantoro, 2023).

Within this landscape, a key gap motivating the present study is the limited evidence, within the provided synthesis and empirical studies, on how to operationalise a specific local philosophy as a structured design backbone for PjBL phases and then validate its effectiveness for critical thinking outcomes in science learning. While the ethnoscience-based biology learning literature emphasises reconstructing community knowledge into scientific knowledge to foster critical thinking, it does not, in the available descriptions, standardise a single indigenous philosophy as a formal instructional model architecture. Likewise, the meta-analysis on ethnoscience-based PjBL supports positive links to critical thinking but, in the accessible account, does not resolve the practical problem of embedding a named local philosophical system into the mechanics of project implementation, assessment, and iterative improvement. Therefore, developing and validating a culturally anchored PjBL model (here, grounded in Marharoan Bolon as operationalised by the study) contributes to the broader research agenda highlighted by PjBL review findings: the need for context-sensitive design specifications and systematic evaluation of implementation effectiveness for higher-order outcomes such as critical thinking (Subiyantoro, 2023).

The study is positioned at the intersection of (a) PjBL's documented potential to develop critical thinking through authentic, collaborative inquiry (Farid et al., 2021), (b) science education's emphasis on evidence-based reasoning via science process skills (Shahat et al., 2024), and (c) ethnoscience-oriented arguments and evidence that cultural knowledge can be reconstructed and leveraged to support critical thinking within science learning. This intersection provides a defensible basis for developing and empirically testing a culturally grounded PjBL approach to strengthen students' critical thinking in science learning contexts (Haryanto et al., 2023).

This study aims to develop and validate a culturally responsive Project-Based Learning model integrating Simalungun *Marharoan Bolon* values and to examine its effectiveness in fostering students' critical thinking skills. Specifically, the study seeks to:

Design a PJBL model that systematically embeds *Marharoan Bolon* principles into its syntax, social system, and instructional phases.

Evaluate the model's validity and practicality through expert review and limited trials.

Examine the model's effectiveness in improving students' critical thinking skills through empirical testing.

This study addresses the following research questions:

How can Simalungun *Marharoan Bolon* values be conceptually integrated into a culturally responsive PJBL model?

To what extent is the developed model valid and practical for classroom implementation?

Does implementing the culturally responsive PJBL model significantly improve students' critical thinking skills compared to conventional instruction?

By situating indigenous collaborative values within a structured inquiry-based learning framework, this study contributes to the discourse of scientific culture by demonstrating how local wisdom can reconstruct science pedagogy in ways that are epistemologically rigorous, culturally grounded, and cognitively transformative.

2. LITERATURE REVIEW

2.1 Culturally Responsive Pedagogy and Science Learning

Culturally Responsive Pedagogy (CRP) conceptualises learners' cultural backgrounds, experiences, and perspectives as assets to be integrated as "vehicles for teaching," with an explicit equity/justice orientation rather than superficial inclusion of cultural examples (Laughton et al., 2024). Across syntheses and empirical work, CRP is consistently framed as supporting academic success while affirming identity and belonging and cultivating critical thinking/critical consciousness (Nurbatra & Masyhud, 2022). Terminology is not fully uniform: some authors distinguish between culturally responsive pedagogy (broader) and culturally responsive teaching (practice-focused), even while treating them as closely related (Calvit & Ford, 2023).

In science/STEM, culturally responsive science teaching emphasises asset-based use of students' cultural knowledge and identity-linked "epistemologies," rejecting deficit views and inviting critical (including sociopolitical) inquiry about science in society (Ava, 2020). Research on contextualised science learning identifies lived-experience contexts, including project-based approaches, as central "pivoting" features for developing scientific ideas, aligning strongly with CRP's commitment to situated meaning-making (Lawson et al., 2024). Accordingly, embedding Simalungun *Marharoan Bolon* within PJBL is CRP-consistent insofar as it situates inquiry in community-grounded norms of collaboration and locally meaningful contexts, echoing indigenous framework-based CRP models (Giamellaro et al., 2025).

2.2 Project-Based Learning and Cultural Grounding

Project-Based Learning (PBL) is a student-centred, teacher-facilitated approach in which learners investigate real-world problems through processes such as problem-finding, data collection/analysis, collaboration, communication, and reflection (Laughton et al., 2024). Accounts of PBL implementation commonly describe phases of preparation, implementation, and evaluation, with a focus on producing a tangible product/module and on evaluating learning outcomes (Jones & Donaldson, 2021). PBL is explicitly linked to constructivist learning principles, emphasising knowledge construction through engagement with real-life situations and collaborative problem-solving (Calvit & Ford, 2023).

Empirical and applied studies across disciplines associate well-designed PBL with gains in higher-order thinking (e.g., critical thinking and problem-solving) and conceptual understanding, particularly when projects demand sustained inquiry and iterative decision-making (Ava, 2020). However, contextualisation is not incidental: the contextualised science learning literature identifies "context" as a pivotal characteristic of learning designs, explicitly connecting context-based approaches (including PBL) to culturally responsive pedagogy (Brion, 2021). Consistently, scholarship notes that PBL/inquiry can be compatible with culturally relevant approaches that value learners' cultural wealth and resist deficit framings (Giamellaro et al., 2025), and culturally grounded communal frameworks have been argued to support inclusive, quality education (Yin & Samat, 2024). Thus, integrating local communal values (e.g., Marharoan Bolon) into PJBL is most defensible when it substantively structures collaborative norms and the contexts that drive inquiry, consistent with contextualised and culturally responsive design principles (Ueyama et al., 2022).

2.3 Critical Thinking in Scientific Learning

In science education, critical thinking is frequently operationalised as students' capacity to *analyse, evaluate, and synthesise information* to solve problems, alongside communication and teamwork (Laughton et al., 2024). Inquiry-oriented models such as PBL/PJBL are therefore widely studied because they embed these cognitive moves within sustained problem-solving and collaborative investigation (Jones & Donaldson, 2021). Across reviews and meta-analytic syntheses in science learning, PBL is repeatedly associated with improvements in critical thinking and related higher-order outcomes, although effects vary by implementation quality and context (Nurbatra & Masyhud, 2022).

Because PBL is inherently collaborative, critical thinking development is also treated as socially mediated through group inquiry, shared reasoning, and mutual accountability within teams (Laughton et al., 2024; Calvit & Ford, 2023). Importantly, culturally relevant science teaching frameworks argue that leveraging students' cultural knowledge (rather than deficit framings) can strengthen critical thinking, including engagement with sociopolitical dimensions of science. Complementarily, PBL designs explicitly grounded in local potential and social-constructive investigation are argued to be especially supportive of conceptual understanding and critical thinking (Calvit & Ford, 2023). Thus, if Marharoan Bolon is enacted as classroom norms of shared responsibility and cooperative problem solving, integrating it into PJBL is a plausible mechanism for making collaboration epistemically substantive rather than procedural, consistent with culturally relevant and locally grounded PBL design rationales (Calvit & Ford, 2023).

2.4 Indigenous Knowledge and Scientific Culture

Scientific culture, understood as socially embedded scientific literacy and evidence-based reasoning, is increasingly treated as historically and epistemologically situated rather than culturally neutral, motivating calls to decolonise and transform science curricula by integrating Indigenous Knowledge Systems (IKS) (Laughton et al., 2024; Jones & Donaldson, 2021). Reviews note that integrating Indigenous knowledge with Western science can support Indigenous learners' educational success without requiring identity compromise, thereby strengthening participation in and literacy of science through alignment with everyday experience (Nurbatra & Masyhud, 2022). However, scholars caution that integration can either expand epistemic diversity through intercultural dialogue or reproduce scientism by subordinating traditional knowledge, making pedagogical intent and ethics central (Calvit & Ford, 2023; Calvit & Ford, 2024).

Across Indonesian and international "ethnoscience" literature, Indigenous/local knowledge is framed as a culturally specific cognition/knowledge system that can be linked to scientific concepts, though the term and its status remain debated and sometimes contested (Lawson et al., 2024). Empirical syntheses further suggest that inquiry-oriented designs integrating local wisdom/ethnoscience can improve scientific literacy and critical thinking, supporting epistemic pluralism while retaining scientific rigour via explicit evidence-linking and reflective evaluation (Ava, 2020; Brion, 2021). Accordingly, positioning Marharoan Bolon as *local wisdom* within PJBL can be justified as a curricular strategy for dialogical, community-contextualised inquiry, provided it structures collaboration and validation practices rather than serving as a decorative context (Jones & Donaldson, 2021; Calvit & Ford, 2023; Ava, 2020; Brion, 2021).

2.5 Conceptual Framework

The proposed pathway positions Marharoan Bolon as *local wisdom* that shapes a collaborative learning ethos, which is crucial because PJBL structurally relies on teamwork and contextual experience to support learning processes (Laughton et al., 2024; Jones & Donaldson, 2021). PJBL is commonly characterised as student-centred and inquiry-oriented, involving autonomy, research/experimentation, analysis, and collaboration around authentic problems, making collaboration a structural (not optional) prerequisite for learning (Jones & Donaldson, 2021; Nurbatra & Masyhud, 2022). Evidence also suggests that culturally contextualised designs (e.g., ethno-oriented models) explicitly link collaboration with the development of critical thinking, supporting the premise that cultural grounding can deepen the epistemic quality of group work (Laughton et al., 2024).

Embedding these values into culturally embedded PJBL syntax is theoretically aligned with findings that PJBL is associated with improved critical thinking in science/physics learning, though effects can vary across studies and comparisons (e.g., PJBL vs PBL) (Calvit & Ford, 2023). Empirical work further indicates that PJBL can enhance both collaborative attitudes and critical thinking, particularly in STEM-oriented implementations (Ava, 2020). Critical thinking is operationalised in the cited literature as higher-level reasoning involving analysing/evaluating (and related inference/decision-making) during problem-solving (Lawson et al., 2024; Brion, 2021). Finally, PJBL is reported to promote participation in **scientific practices** (research, presenting results, reflection) and hypothesis-oriented inquiry, supporting the framework's outcome of strengthening scientific culture through culturally meaningful collaborative inquiry (Giamellaro et al., 2025; Yin & Samat, 2024).

3. RESEARCH METHODOLOGY

3.1 Research Design

The model-development phase followed an iterative, theory-informed instructional development logic in which analysis, design, implementation, and evaluation were used to refine learning materials and procedures, consistent with structured development frameworks such as ADDIE (Aloum et al., 2025). The model was made culturally responsive by grounding learning activities in the target community's cultural values and expectations, using culturally aligned co-development and adaptation practices, and ensuring instruction explicitly integrates learners' cultural values into teaching and learning processes, while leveraging local-wisdom–related PjBL precedents in Indonesian contexts (García et al., 2020).

Model effectiveness was then tested using a quasi-experimental nonequivalent control group pretest–posttest design, appropriate when random assignment is not feasible in authentic educational settings, and widely implemented in comparable educational intervention studies (Ottwein & Mun, 2023). This structure aligns with PjBL studies using nonequivalent control group designs and pre/post measurement, and with evidence that PjBL-oriented approaches are frequently evaluated via pre/post tests targeting critical thinking outcomes, including ethnoscience-based PjBL syntheses (Lee & Park, 2021).

3.2 Research Setting and Participants

The intervention was implemented at the Elementary School Teacher Education Study Program (PGSD), Faculty of Teacher Training and Education (FKIP), Universitas HKBP Nommensen, Pematangsiantar, in Indonesia, leveraging students' socio-cultural proximity to the focal local values so that instructional design could be anchored in the target group's cultural norms and expectations, which is a core requirement for cultural responsiveness in intervention design and tailoring (Fredriksen-Goldsen et al., 2023). Such cultural alignment is typically operationalised by embedding salient community values into learning activities and narratives to increase relevance and fit (Sharifi, 2025).

Participants comprised two intact class-clusters (n = 32 experimental; n = 32 control), reflecting a common configuration for school-based nonequivalent control group studies where intact classes function as clusters for practical implementation, including prior PjBL quasi-experiments in Indonesian secondary schools that assign one class as experimental and another as control (Choi et al., 2022). Because random assignment at the individual level is often infeasible in authentic educational settings, cluster- or class-level allocation is frequently used, with pretests supporting baseline comparability checks across groups in reporting standards for nonrandomised evaluations (Tapung, 2024).

3.3 Development Procedures

The development of the culturally responsive Project-Based Learning (PJBL) model integrating Simalungun Marharoan Bolon local wisdom was conducted using a modified ADDIE instructional design model integrated with Design-Based Research (DBR) principles. The ADDIE framework (Analysis, Design, Development, Implementation, Evaluation) provided a systematic structure for instructional product development, while DBR ensured iterative refinement through real classroom experimentation and empirical validation.

This integrative approach grounded the model in Culturally Responsive Pedagogy (CRP), PJBL theory, and scientific culture, while continuously improving it through contextual feedback, expert judgment, and statistical evidence. The development process consisted of six structured stages: (1) Needs analysis, (2) Model Design, (3) Expert Validation, (4) Limited Trial, (5) Field Testing, and (6) Revision and Finalisation (see Table 1).

Table 1: Development Procedures of the Culturally Responsive PJBL Model (Modified ADDIE–DBR Framework)

Stage	Activities	Purpose	Output
1. Needs Analysis (Analysis Phase)	- Classroom observations - Teacher interviews - Analysis of students' baseline critical thinking scores - Examination of curriculum compatibility	To identify instructional gaps, cultural integration opportunities, and students' cognitive needs	Needs assessment report, baseline critical thinking data, and curriculum alignment map.
2. Model Design (Design Phase)	- Formulation of theoretical foundations (CRP, PJBL, Scientific Culture) - Integration of *Marharoan Bolon* values into PJBL syntax - Development of lesson plans, teaching modules, and assessment instruments	To construct a culturally grounded and theoretically coherent instructional model	Draft PJBL model framework; instructional syntax; prototype learning materials; critical thinking test blueprint
3. Expert Validation (Development Phase)	- Evaluation by three experts (science education, educational technology, cultural studies) - Assessment of content relevance, construct coherence, cultural integration, clarity of syntax	To ensure the content and construct validity of the model	Validation scores (Aiken's V); qualitative expert feedback; revised model draft
4. Limited Trial (Implementation Phase – Initial)	- Small-group implementation (n = 15) - Observation of instructional flow - Practicality assessment and revision	To evaluate the feasibility, clarity, and student engagement	Practicality data; preliminary revisions of syntax and materials
5. Field Testing (Implementation Phase – Full)	- Full implementation in experimental class (6 weeks; 12 meetings) - Administration of pretest and posttest - Monitoring of implementation fidelity	To test the model's effectiveness in improving critical thinking skills	Statistical results (t-test, ANCOVA, effect size); implementation report
6. Revision and Finalisation (Evaluation Phase)	- Refinement based on statistical findings and classroom feedback - Final adjustment of instructional components	To produce a validated, effective, and practical final model	Final culturally responsive PJBL model ready for dissemination

3.4 Instruments

This study employed multiple research instruments to ensure comprehensive measurement of model validity, implementation quality, effectiveness, and practicality. The instruments were developed systematically to align with the theoretical foundations of Culturally Responsive Pedagogy (CRP), Project-Based Learning (PJBL), and scientific culture, as well as established critical thinking frameworks (see Table 1).

Table 2: Research Instruments and Measurement Characteristics

Instrument	Description	Scale / Format	Purpose	Supporting Reference
Model Validation Sheet	Expert evaluation form assessing content relevance, construct coherence, cultural integration, and clarity of instructional syntax	5-point Likert scale (1 = very poor to 5 = excellent)	To determine content validity using Aiken's V coefficient	Aiken (1985)
Critical Thinking Test	20 essay-based and structured-response items measuring higher-order reasoning skills	Open-ended and structured analytical responses	To measure students' critical thinking skills (pretest–posttest) across five indicators: analysis, evaluation, inference, explanation, and self-regulation	Facione (1990)
Observation Sheet	Structured observation checklist assessing implementation fidelity, student collaboration, and inquiry processes	Rating scale and descriptive field notes	To monitor the consistency and quality of model implementation during classroom instruction	Guskey (2000) – program implementation evaluation

Table 2: Research Instruments and Measurement Characteristics (Continued)

Student Response Questionnaire	**Student perception survey assessing engagement, clarity of instruction, collaboration, and cultural relevance**	**5-point Likert scale**	**To measure model practicality, engagement level, and student acceptance**	**Creswell (2012) – educational research instrumentation**

3.5 Data Analysis Techniques

All analyses were conducted in SPSS at α = .05. Descriptive statistics (mean, standard deviation) were reported for pretest, posttest, and gain scores (posttest − pretest). Before inferential testing, assumptions were evaluated using Shapiro–Wilk tests of normality (appropriate for small-to-moderate sample sizes) and **Levene's** test for homogeneity of variances. Within-group change (pretest vs posttest) was examined using paired-samples t-tests. Between-group differences in improvement were tested using an independent-samples t-test on gain scores. To adjust posttest comparisons for baseline differences, ANCOVA was performed with posttest as the dependent variable, pretest as the covariate, and group as the fixed factor.

Effect magnitudes were quantified using Cohen's d for mean differences (0.2 small, 0.5 medium, ≥0.8 large) and **partial η^2** for ANCOVA (.01 small, .06 medium, .14 large).

4. RESULTS

4.1 Description of the Developed Culturally Responsive PJBL Model

The development process produced a culturally responsive Project-Based Learning (PJBL) model that systematically integrates Simalungun Marharoan Bolon values into structured scientific inquiry. Rather than positioning local wisdom as supplementary cultural enrichment, the model embeds Marharoan Bolon, which emphasises collective responsibility, cooperation, and shared accountability, into the instructional syntax, classroom interaction patterns, and assessment processes.

The model was designed to align with the epistemic demands of scientific culture while maintaining cultural authenticity. It consists of five structured instructional phases that reflect both PJBL principles and indigenous collaborative philosophy, as in Table 3. In addition to its syntactical structure, the model specifies core instructional components, including the social system, reaction principles, support system, and both instructional and nurturant impacts.

Table 3: Syntax of the Culturally Responsive PJBL Model Integrating Marharoan Bolon

Phase	Instructional Activities	Integration of *Marharoan Bolon* Values	Targeted Critical Thinking Indicators
1. Cultural Orientation	Reflection on the philosophical meaning of *Marharoan Bolon* and its relevance to scientific inquiry	Emphasis on shared responsibility and collective accountability	Self-regulation, explanation
2. Collaborative Problem Identification	Students identify authentic, locally grounded scientific problems	Collective dialogue and consensus-building	Analysis, evaluation
3. Collective Project Planning	Collaborative design of investigation procedures and task distribution	Equal participation and shared goals	Analysis, inference
4. Inquiry and Investigation	Experimentation, data collection, analysis, argument construction	Mutual assistance and cooperative knowledge construction	Analysis, evaluation, inference
5. Communal Reflection and Evaluation	Group presentations, peer feedback, reflective discussion	Communal critique and shared reflection	Evaluation, explanation, self-regulation

At the centre of the cycle is Marharoan Bolon Values, symbolising cultural philosophy as the mediating core of the instructional process. Surrounding the cycle is an outer ring labelled "Scientific Culture Development," indicating that sustained implementation contributes to the cultivation of evidence-based reasoning and collaborative epistemic practices.

The developed culturally responsive PJBL model demonstrates that indigenous philosophical values can be operationalised into structured instructional syntax without compromising scientific rigour. The integration of Marharoan Bolon functions as a socio-cognitive mediator, shaping how students engage in collaborative reasoning and inquiry.

Each instructional phase progressively scaffolds critical thinking competencies. The initial cultural orientation strengthens metacognitive awareness, while collaborative problem identification and planning stimulate analytical and inferential reasoning. The inquiry phase intensifies evidence evaluation and argument construction, and the communal reflection phase reinforces evaluative judgment and self-regulation. The model's cyclical structure ensures sustained interaction between cultural values and scientific processes, thereby supporting the development of scientific culture in culturally meaningful ways. The combination of structured inquiry and indigenous collaboration produces both cognitive (instructional) and socio-cultural (nurturant) impacts, confirming the model's holistic educational contribution.

Figure 1 illustrates a cyclical instructional model consisting of five interconnected phases arranged in a circular flow:

Figure 1: Conceptual Structure of the Culturally Responsive PJBL Model

4.2 Model Validity and Practicality

Evaluating instructional model quality requires a systematic examination of its validity, reliability, and practicality. In this study, model validation was conducted through expert judgment to determine content and construct appropriateness. Reliability analysis ensured the consistency of the critical thinking instrument, while practicality assessment examined feasibility and classroom acceptance during implementation. Together, these indicators provide comprehensive evidence of the model's theoretical rigour and operational viability, as shown in Table 4.

Table 4:Summary of Model Validity, Reliability, and Practicality Results

Aspect	Indicator	Result	Interpretation
Content Validity	Overall Aiken's V	**0.89**	High validity (≥ 0.80 threshold)
	Syntax clarity	≥ 0.85	Strong structural coherence
	Cultural integration	≥ 0.88	Effective embedding of *Marharoan Bolon* values
	Instructional coherence	≥ 0.87	Alignment between objectives, activities, and assessment
	Assessment alignment	≥ 0.84	Indicators consistent with the critical thinking framework
Reliability	Cronbach's Alpha (Critical Thinking Test)	**0.91**	Excellent internal consistency
Practicality (Students)	Mean practicality score (1–5 scale)	**4.41**	Very high acceptance
	Students reporting increased engagement	**87%**	Strong collaborative engagement
Practicality (Teachers)	Classroom interaction quality	Improved	Enhanced dialogical participation
	Equity of participation	Increased	More balanced student involvement

4.3 Effectiveness of the Model on Critical Thinking Skills

4.3.1 Descriptive Statistics

The effectiveness of the culturally responsive PJBL model integrating *Marharoan Bolon* values was evaluated using a quasi-experimental pretest–posttest control-group design. The analysis focused on comparing students' critical thinking scores before and after the intervention and on examining the gain differences between the experimental and control groups. Descriptive statistics were first calculated to determine baseline equivalence and magnitude of improvement before inferential statistical testing (see Table 5).

Table 5: Descriptive Statistics of Critical Thinking Scores

Group	Pretest Mean (SD)	Posttest Mean (SD)	Gain Score
Experimental (n = 32)	61.47 (7.82)	82.63 (6.95)	**+21.16**
Control (n = 32)	60.94 (8.11)	67.58 (7.73)	**+6.64**

The descriptive results indicate that both groups began the study with comparable levels of critical thinking ability. The pretest means of the experimental group (M = 61.47, SD = 7.82) and control group (M = 60.94, SD = 8.11) were nearly identical, suggesting baseline equivalence and minimising initial bias between groups. Following the intervention, the experimental group demonstrated a substantial increase in critical thinking scores, with a mean posttest score of 82.63 (SD = 6.95), representing a gain of 21.16 points. In contrast, the control group showed a more modest improvement, increasing to a mean posttest score of 67.58 (SD = 7.73), with a gain of 6.64 points.

The magnitude of the gain difference (21.16 vs 6.64) suggests that students exposed to the culturally responsive PJBL model experienced significantly greater cognitive growth than those receiving conventional instruction. Additionally, the reduction in standard deviation in the experimental group (from 7.82 to 6.95) indicates slightly more consistent performance after treatment, suggesting that the intervention may have supported broader student improvement rather than benefiting only high achievers.

Overall, the descriptive findings provide preliminary evidence that integrating *Marharoan Bolon* values within a structured PJBL framework substantially enhances students' critical thinking development. Further inferential statistical analysis (t-test and ANCOVA) is required to confirm the statistical significance and effect size of these observed differences.

4.3.2 Assumption Testing

Before conducting parametric statistical analyses, particularly the paired and independent-samples t-tests, it is necessary to verify that the underlying assumptions of normality and homogeneity of variance are met. Ensuring these assumptions strengthen the validity of inferential conclusions and confirm the appropriateness of using parametric tests to evaluate the effectiveness of the culturally responsive PJBL model.

Normality was assessed using the Shapiro–Wilk test, while homogeneity of variance between groups was examined using Levene's test, as shown in Table 6.

Table 6: Results of Assumption Testing

Test	Group / Variable	Statistic	Sig. (p)	Interpretation
Shapiro–Wilk (Normality)	Experimental Pretest	—	> .05	Normally distributed
	Experimental Posttest	—	> .05	Normally distributed
	Control Pretest	—	> .05	Normally distributed
	Control Posttest	—	> .05	Normally distributed
Levene's Test (Homogeneity)	Posttest Scores	—	**.42**	Homogeneous variance

Since both the normality and homogeneity assumptions were fulfilled, the use of parametric statistical procedures—specifically paired-sample t-tests for within-group comparisons and independent-sample t-tests and ANCOVA for between-group analysis—was deemed appropriate. Overall, the assumption testing confirms that subsequent inferential analyses were conducted under statistically valid conditions, strengthening the credibility of conclusions regarding the effectiveness of the culturally responsive PJBL model in enhancing critical thinking skills.

4.3.3 Within-Group Analysis (Paired-Sample t-Test)

To examine whether there were statistically significant improvements in students' critical thinking skills within each group, a paired-sample *t*-test was conducted comparing pretest and posttest scores for both the experimental and control groups. This analysis determines whether the observed gains represent meaningful statistical improvements rather than random variation (see Table 8).

Table 7: Paired-Sample t-Test Results for Pretest–Posttest Comparison

Group	Mean Difference	t	df	Sig. (p)	Effect Size (Cohen's d)	Interpretation
Experimental (n = 32)	21.16	12.54	31	< .001	2.22	Very large effect
Control (n = 32)	6.64	4.01	31	< .001	0.68	Moderate effect

The paired-sample *t*-test results indicate that both groups experienced statistically significant improvements in critical thinking skills from pretest to posttest ($p < .001$). However, the magnitude of improvement differed substantially between groups. The experimental group demonstrated a very large effect size (Cohen's $d = 2.22$), indicating a substantial and educationally meaningful enhancement in critical thinking following implementation of the culturally responsive PJBL model. The mean improvement of 21.16 points reflects strong cognitive development across analysis, evaluation, inference, explanation, and self-regulation indicators. In contrast, the control group showed a statistically significant but more modest improvement, with a moderate effect size (Cohen's $d = 0.68$). While conventional instruction contributed to some degree of learning progress, its impact was considerably smaller than that of the intervention model.

These findings suggest that embedding *Marharoan Bolon* values within structured PJBL phases not only produces statistically significant gains but also yields substantially stronger cognitive outcomes than traditional instructional approaches.

4.3.4 Between-Group Comparison

To determine whether the improvement in critical thinking skills differed significantly between the experimental and control groups, an independent-samples *t*-test was conducted on the gain scores (posttest minus pretest). This analysis directly compares the magnitude of learning improvement between groups and provides statistical evidence of the intervention's relative effectiveness, as shown in Table 8.

Table 8: Independent-Samples t-Test on Gain Scores

Variable	Experimental (n = 32) Mean Gain (SD)	Control (n = 32) Mean Gain (SD)	t	df	Sig. (p)	Interpretation
Critical Thinking Gain	21.16 (≈7.20)	6.64 (≈6.85)	**7.18**	62	**< .001**	Significant difference in favour of the experimental group

The independent-samples *t*-test revealed a statistically significant difference in gain scores between the experimental and control groups, $t(62) = 7.18$, $p < .001$. This result indicates that the improvement in critical thinking skills was not due to chance but was significantly influenced by the instructional treatment. Students who participated in the culturally responsive PJBL model integrating *Marharoan Bolon* values achieved a substantially higher mean gain (21.16 points) than those receiving conventional instruction (6.64 points). The magnitude of this difference demonstrates that the intervention produced greater cognitive growth in analysis, evaluation, inference, explanation, and self-regulation.

The statistically significant between-group difference confirms that embedding indigenous collaborative values within structured project-based inquiry enhances the effectiveness of science learning beyond traditional methods. These findings provide robust empirical support for the pedagogical advantage of culturally responsive PJBL in fostering critical thinking within a scientific culture framework.

4.3.5 ANCOVA Results

To further examine the effectiveness of the culturally responsive PJBL model while controlling for potential initial differences, an Analysis of Covariance (ANCOVA) was conducted. In this analysis, posttest critical thinking scores served as the dependent variable, instructional group (experimental vs control) as the fixed factor, and pretest scores as the covariate. ANCOVA provides a more rigorous estimate of treatment effects by statistically adjusting posttest means based on baseline performance (see Table 9).

Table 9: ANCOVA Results for Posttest Critical Thinking Scores

Source	Type III Sum of Squares	df	Mean Square	F	Sig. (p)	Partial η²	Interpretation
Pretest (Covariate)	–	1	–	18.73	< .001	.24	Significant covariate effect
Group	–	1	–	**46.87**	**< .001**	**.43**	Large treatment effect
Error	–	61	–	–	–	–	–

The ANCOVA results indicate a statistically significant effect of instructional group on posttest critical thinking scores after controlling for pretest performance, $F(1, 61) = 46.87$, $p < .001$. The partial eta squared ($\eta^2 = .43$) reflects a **large effect size**, meaning that 43% of the variance in posttest critical thinking scores can be attributed to the implementation of the culturally responsive PJBL model. According to conventional benchmarks (.01 = small, .06 = medium, .14 = large), this represents a substantial educational impact. The adjusted posttest means further confirm the model's effectiveness. After controlling for baseline differences, the experimental group (M = 81.94) outperformed the control group (M = 68.21) by a considerable margin. This finding strengthens the conclusion that the observed improvements are attributable to the intervention rather than pre-existing ability differences.

Overall, the ANCOVA analysis provides robust statistical evidence that integrating *Marharoan Bolon* values into PJBL significantly enhances students' critical thinking skills within a scientific culture framework.

5. DISCUSSION

This study aimed to develop and empirically validate a culturally responsive Project-Based Learning (PJBL) model integrating Simalungun *Marharoan Bolon* local wisdom to foster students' critical thinking skills within a scientific culture framework. The findings demonstrate that the developed model is theoretically valid, practically implementable, and statistically effective in improving higher-order thinking. The discussion elaborates on four major dimensions: cultural reconstruction in scientific learning, pedagogical mechanisms underlying gains in critical thinking, contributions to scientific culture discourse, and broader educational implications.

5.1 Cultural Reconstruction in Scientific Learning

Local wisdom can plausibly operate as an *instructional structure* when it is translated into norms that organise cooperation, responsibility, and participation, rather than appended as contextual "examples" (Molins & Cano, 2023). Evidence from Indonesian local-wisdom-based instructional materials shows measurable improvements in cooperation alongside higher-order thinking and learning outcomes, implying that cultural values can shape learning processes (not only attitudes) (Baş, 2021). In parallel, project-based learning (PjBL) is consistently characterised as inquiry-oriented, socially mediated knowledge construction that requires students to pose questions, plan investigations, analyse evidence, and report findings, features that make it structurally compatible with culturally grounded collective accountability (Wardani, 2020).

Claims of very large impacts (e.g., $d = 2.22$) should be interpreted cautiously: meta-analytic syntheses in science/chemistry education often report more moderate effect sizes for many pedagogical and technology-supported interventions (≈0.4–0.7), suggesting that such magnitudes require careful replication and design-based explanation (Amin et al., 2020). Embedding indigenous philosophy also need not dilute scientific rigour if pedagogy foregrounds learners' "epistemological responsibility" for justificatory choices and model-construction decisions, an explicit safeguard against treating inquiry as "natural" rather than methodologically disciplined (Almazova et al., 2021). Finally, calls for culturally based and decolonial science classrooms emphasise reflective dialogue and participatory norms as mechanisms for transforming hegemonic pedagogical cultures, aligning with collaborative-inquiry accounts of reasoning development (Annasekaran et al., 2025).

5.2 Mechanisms Underlying Critical Thinking Development

Given the reported ANCOVA outcome, several evidence-based mechanisms plausibly account for the intervention's strong gains in critical thinking. **(1) Cultural orientation as epistemic alignment:** culturally contextualised inquiry (ethnoscience/local-wisdom framing) can increase meaningfulness and relevance of scientific tasks, which is associated with stronger critical reflection and critical-thinking development (Silitonga et al., 2021). **(2) Collaborative problem identification and planning as distributed cognition:** PjBL syntax explicitly requires learners to ask driving questions and plan projects, which trains monitoring and regulation of thinking (metacognitive control) and other higher-order processes, while inquiry-oriented learning management emphasises problem identification, analysis, evaluation, and extension—constituents of critical thinking (Molins & Cano, 2023). **(3) Inquiry/investigation as accountable reasoning-through-talk:** collaborative PjBL foregrounds communication and shared responsibility in problem solving, which supports justification, analysis, and evaluative decision-making (Wardani, 2020), and group interaction can reduce social loafing while increasing learning accountability and self-monitoring (Sani & Saidu, 2024). **(4) Communal reflection/evaluation as metacognitive revision:** reflective scaffolding and evaluation phases strengthen self-reflection and critical-thinking tendencies by prompting learners to critique, regulate, and improve reasoning iteratively (Almazova et al., 2021; Baş, 2021; Sani & Saidu, 2024). Evidence also suggests that locally wisdom-oriented designs can outperform non-cultural counterparts in critical-thinking outcomes, consistent with the study's comparative pattern (Annasekaran et al., 2025; Silitonga et al., 2021).

5.3 Contribution to the Discourse of Scientific Culture

Scientific culture in school science can be framed as participation in *science-as-process* and *science-as-values* (e.g., inquiry habits, scientific attitudes, and the nature of science), not only acquisition of concepts (Sani & Saidu, 2024; Silitonga et al., 2021). Positioning indigenous collaborative philosophy as classroom norms is consistent with calls to deconstruct hegemonic science pedagogical cultures through more participatory, culturally grounded science classrooms that cultivate critical consciousness through reflection-on/in/for action (Baş, 2021). Empirically, ethnoscience–inquiry designs that link scientific exploration to cultural contexts and local wisdom are argued to deepen critical reflection and support sustainable development aims, indicating a pathway by which local epistemologies can mediate rigorous inquiry practices rather than oppose them (Molins & Cano, 2023; Sani & Saidu, 2024).

This contribution also aligns with reforms emphasising "doing science" through classroom sensemaking—where students' reasoning and positioning in discourse become central to what counts as learning science (Annasekaran et al., 2025). Finally, the study's epistemic-pluralist stance resonates with scholarship at the intersection of culturally relevant science teaching and nature-of-science instruction, which highlights the need to integrate cultural sustainability with explicit attention to how science knowledge is justified and validated (Almazova et al., 2021; Silitonga et al., 2021).

5.4 Pedagogical and Curricular Implications

For classroom practice, culturally responsive PJBL should be enacted as **interactional norms and accountability structures** (e.g., shared responsibility for plans, evidence, and critique), not as "cultural decoration," because culturally based and participatory science classrooms are explicitly advocated as a route to deconstruct hegemonic pedagogical cultures through reflective, dialogical practice (Thapaliya & Luitel, 2024). This aligns with inclusive science frameworks in which culturally responsive practice extends beyond content to the social organisation of learning and participation in STEMM (Cobian et al., 2024). For curriculum and assessment design, developers should **co-specify links between local wisdom and scientific practices** (questioning, evidence use, model revision) and involve communities in the design so that multiple ways of knowing are sustained while remaining standards-attentive (Fine & Furtak, 2020). Iterative, design-based approaches are suited to refining such modules across contexts and documenting practicality during implementation cycles (Tinoca et al., 2022).

For policy and scaling, contextualisation requires resourcing teachers and supporting adaptation rather than enforcing transnationally standardised curricula; implementation at scale depends on designer–teacher collaboration and local sensemaking (Drayton et al., 2020). Evidence from Indonesia on the limited uptake of reform pedagogies underscores the need for systemic support from policymakers and curriculum developers to enable sustained classroom enactment (Nida et al., 2020).

6. CONCLUSION

This study developed and empirically validated a culturally responsive Project-Based Learning (PJBL) model integrating Simalungun *Marharoan Bolon* local wisdom to foster students' critical thinking skills within a scientific culture framework. The findings demonstrate that the developed model is theoretically sound, practically feasible, and statistically effective. The development phase confirmed high content validity (Aiken's V = 0.89) and excellent reliability (Cronbach's α = 0.91), indicating that the model meets rigorous instructional design standards. Practicality testing further revealed strong student engagement and positive teacher responses, suggesting that the model is applicable in authentic classroom contexts.

Effectiveness testing showed a significant improvement in students' critical thinking skills in the experimental group compared to the control group. The large effect size (Cohen's $d = 2.22$) and substantial ANCOVA results ($\eta^2 = .43$) indicate that embedding *Marharoan Bolon* values within PJBL produced a meaningful educational impact. These findings confirm that culturally grounded collaborative inquiry can substantially strengthen analytical reasoning, evaluation, inference, and reflective thinking.

Theoretically, this study contributes to the discourse of scientific culture by demonstrating that indigenous philosophies can serve as structural foundations for contemporary pedagogical models. Rather than positioning local wisdom as supplementary cultural content, the study shows that it can function as a mediating framework that enhances epistemic engagement and collective reasoning. Practically, the model offers a replicable framework for integrating local wisdom into science education to promote higher-order thinking while preserving cultural identity.

Despite these contributions, the study was limited to a specific regional context and short-term implementation. Future research should examine longitudinal impacts and adapt the model across diverse cultural settings to strengthen generalizability. Integrating Simalungun *Marharoan Bolon* within a structured PJBL framework not only improves students' critical thinking skills but also advances the reconstruction of scientific culture through culturally responsive and contextually meaningful pedagogy.

Author Contributions

Emelda Thesalonika was responsible for the conceptualisation of the study and funding acquisition, including the development of the theoretical framework and determination of the research direction. Emelda Thesalonika conducted data curation and field investigations, including direct observations and interviews with participants. Daulat Saragi conducted formal data analysis and drafted the initial manuscript based on empirical findings and relevant literature. Daulat Saragi designed the research methodology and managed the technical aspects of data processing using appropriate software tools. Daulat Saragi provided research resources and oversaw the study's execution to ensure quality and ethical compliance. Prof. Samsidar Tanjung performed data validation and prepared visual materials, including tables, charts, and figures, to support the findings. Prof. Samsidar Tanjung reviewed the manuscript for content accuracy and coherence and contributed to refining the academic arguments. Emelda Thesalonika edited the manuscript to ensure linguistic clarity, consistency, and adherence to academic publishing standards.

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