

Development of Karo Culture-Based Problem-Based Learning Model Assisted by Information Technology to Improve Students' Collaborative Skills and Mathematical Problem-Solving

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HOW TO CITE:

Novi Tari Simbolon, Bornok Sinaga,
Abil Mansyur (2026).
Development of Karo Culture-Based
Problem-Based Learning Model
Assisted by Information Technology
to Improve Students' Collaborative
Skills and Mathematical Problem-
Solving.
International Journal of Special
Education, 41(24s), 599-616

ABSTRACT:

Mathematics education in Indonesia faces major challenges in developing students' higher-order thinking skills, collaborative competence, and mathematical problem-solving abilities. PISA 2022 ranked Indonesia 72nd out of 79 countries, with only 18% of students reaching Level 2, far below the OECD average of 69%. This crisis is exacerbated by minimal use of local cultural contexts in instructional design and limited digital technology integration.

This study develops a Karo culture-based Problem Based Learning model assisted by information technology, called PBL-Sitelu, to improve high school students' collaboration and mathematical problem-solving. Using an R&D design with the ADDIE framework, expert validation was conducted through three-cycle Delphi technique. The research was carried out in North Sumatra high schools during the even semester of 2025/2026, involving mathematics students in the Karo cultural area through purposive sampling.

Data were collected via expert validation sheets, collaboration questionnaires, problem-solving tests, student response surveys, and observations. Validity was measured by expert agreement percentage; practicality by teacher implementation scores and student responses; effectiveness through T-tests ($p < 0.05$). Results showed validity $> 80\%$, high practicality (score $\geq 3.5/4.0$), and significant improvements in collaboration ($61.4 \rightarrow 82.7$; $p = 0.001$) and problem-solving ($54.2 \rightarrow 79.8$; $p = 0.000$), with student responses $> 85\%$. PBL-Sitelu is proven

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of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).	valid, practical, and effective for secondary mathematics education. Keywords: Problem-Based Learning; ethnomathematics; mathematical problem-solving; collaborative learning; IT-assisted learning.
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1. Introduction

Mathematics education in the 21st century demands more than procedural mastery; it requires students to think critically, collaborate effectively, and solve complex real-world problems. *The Partnership for 21st Century Learning* (P21, 2019) identifies Critical Thinking, Creativity, Collaboration, and Communication as essential for the evolving global economy, yet Indonesian students consistently lag behind their peers, especially in mathematics. Indonesia's Merdeka Curriculum echoes this emphasis, foregrounding critical thinking, collaboration, and contextual learning under the Pancasila Student Profile positioning mathematics as a foundational literacy that must remain sensitive to the cultural diversity of Indonesia's more than 1,300 ethnic groups, the intersection at which this study is situated.

PISA 2022 ranked Indonesia 72nd of 79 countries in mathematics literacy, with only 18% reaching Level 2 against an OECD average of 69%, and almost none reaching Level 5–6, versus 41% in Singapore (OECD, 2022). TIMSS 2023 corroborates weak conceptual understanding (Mullis et al., 2023), while Indonesia ranks 77th of 79 in collaborative problem-solving, averaging only 34 points (OECD, 2023) a chronic, structural pattern attributed to procedural, memorization-heavy teaching, with consequences for workforce readiness in labor markets that increasingly reward teamwork.

Classroom observations in the Karo region confirm this trend: students show fundamental algebraic errors, fail to plan or verify solutions, and rarely collaborate meaningfully, reflecting both weak structured collaborative learning and a disconnect between curricular content and students' lived experiences (Sari & Sembiring, 2021; Hidayat, 2021). These patterns are compounded by large class sizes, limited learning

aids, and an assessment culture privileging speed over reasoning, producing a cycle in which mathematics feels abstract and culturally alien.

Problem Based Learning (PBL), grounded in Vygotsky's (1978) social constructivism and Bruner's discovery learning, positions real problems as an entry point for inquiry and collaboration (Barrow, 1996; Savery, 2015). Yet most Indonesian PBL implementations ignore local cultural context (Rahman et al., 2022; Sembiring, 2020); even where PBL succeeds across diverse tracks (Nopriska et al., 2021), generic scenarios can alienate students from strong ethnic-cultural backgrounds such as the Karo. Closing this gap requires embedding local knowledge systems into mathematical tasks, not merely renaming characters.

The Karo ethnic group offers rich such structures: patterns embedded in architecture, weaving, agriculture, and the tripartite philosophy of *Rakut Sitelu*, which governs community decision-making. Lattice carvings encode symmetry; woven *uis Karo* motifs embed combinatorial logic; terraced fields reflect reasoning about area and resource allocation (Peranginangin et al., 2019; Misfeldt et al., 2019). Complementing this, the Indonesian LMS NusaLink extends PBL's collaboration beyond class time via asynchronous workspaces (Zainuddin & Halili, 2020) an alternative suited to North Sumatra's uneven connectivity.

Therefore, this study asks: *How can a PBL model based on Karo culture assisted by information technology be developed to be valid, practical, and effective in improving the collaborative and mathematical problem-solving skills of high school students?* Following Plomp's (2013) criteria, the study (1) designs and expert-validates a PBL model integrating *Rakut Sitelu*-centered ethnomathematics with NusaLink-based IT scaffolding, called PBL-Sitelu; (2) assesses its practicality for teachers and

students; and (3) evaluates its effectiveness relative to conventional instruction extending ethnomathematical theory and offering the Merdeka Curriculum an evidence-based template for reconciling competency-based learning with cultural diversity.

THEORETICAL BACKGROUND

Problem-Based Learning and constructivist theory

PBL rests on Vygotsky's (1978) social constructivism and Bruner's (1960) discovery learning: understanding arises through inquiry-driven engagement with authentic problems, with the Zone of Proximal Development explaining how peer interaction enables otherwise-inaccessible competencies. Following a cycle of orientation, analysis, investigation, and reflection (Savery, 2015), PBL consistently outperforms didactic instruction on transfer and motivation, even in heterogeneous settings (Nopriska et al., 2021), though unguided discovery risks overwhelming novices without deliberate structuring motivating PBL-Sitelu's explicit five-stage syntax.

Collaborative Learning and Mathematical Problem-Solving

Collaboration denotes a structured social process of communication and shared responsibility (Pratiwi, 2016) that reinforces students' confidence in their own and peers' competence (Rosmawati & Sritresna, 2021), though Indonesian students frequently show unequal participation (Hidayat, 2021). Polya's (1980) four-phase heuristic is typically reduced in practice to execution alone; PBL-Sitelu therefore makes planning and verification explicit and assessable.

Ethnomathematics and Karo culture

Ethnomathematics (D'Ambrosio, 1985; Ernest, 1991) treats mathematics as culturally constructed; embedding such practices in schooling reduces anxiety and enhances transfer (Misfeldt et al., 2019). *Rakut Sitelu* "the bond of three" connects *kalimbubu* (wife-givers), *senina* (clan members), and *anak beru* (wife-takers) in a relational system analogous to Venn-diagram

reasoning and simultaneous equations, anchoring non-routine problems in logic Karo students already live (Sinaga et al., 2008).

Technology-enhanced learning and NusaLink

The TPACK framework (Mishra & Koehler, 2006) requires deliberate alignment of technology with pedagogy (Phungsuk et al., 2021). NusaLink operationalizes this through a contextualized problem repository, collaborative workspaces, formative assessment, and reflective journals alignment, rather than adoption per se, that drives self-regulated learning (Widiastuti, 2019; Zainuddin & Halili, 2020). Together, these strands constitute the framework guiding PBL-Sitelu's design in the following section

2. Methodology

This study uses a research and development (R&D) methodology following the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model, which is very suitable for repetitive construction and validation of instructional models (Nadiyah & Faaizah, 2015; Perry, 2015). The ADDIE framework guides four successive phases:

The ADDIE framework was selected over alternative design-research models because its five iterative phases Analysis, Design, Development, Implementation, and Evaluation map directly onto the study's tripartite validity, practicality, and effectiveness objectives, while its cyclical, revision-oriented structure accommodates the multi-round expert validation and staged trialing that culturally grounded instructional innovations typically require (Nadiyah & Faaizah, 2015; Perry, 2015). Evaluation, in this framework, is not confined to a discrete terminal phase but is embedded formatively within each preceding phase expert panels evaluate the Design and Development outputs, teachers and students evaluate practicality during Implementation's limited trial, and the quasi-experimental field trial constitutes the summative evaluation of effectiveness consistent with Plomp's (2013) recommendation that design research findings be evaluated against

the three interlocking criteria of validity, practicality, and effectiveness.

Analysis phase

The needs analysis was carried out through structured classroom observation, teacher interviews, and student diagnostic assessments in three high schools in the Karo area of North Sumatra during the first semester of 2025/2026. Analysis of national curriculum standard documents (Independent Curriculum) and systematic literature review on the implementation of PBL in Indonesian secondary mathematics education inform the model design parameters.

The needs analysis triangulated three data sources to ensure convergent validity of the identified instructional gaps. Structured classroom observations, conducted using a validated observation protocol across a minimum of six lesson sessions per school, documented the frequency and quality of collaborative activities, the presence or absence of explicit problem-solving scaffolding, and instances of cultural referencing within instructional materials. Semi-structured teacher interviews explored instructors' perceptions of student collaborative competence, familiarity with PBL principles, and prior exposure to culturally contextualized teaching materials. Student diagnostic assessments, comprising open-ended non-routine mathematics items, established baseline problem-solving performance and surfaced characteristic error patterns, including premature calculation without planning, absence of solution verification, and difficulty translating word problems into mathematical representations. These findings were triangulated against a systematic review of the Merdeka Curriculum's mathematics competency standards and the broader Indonesian and international literature on PBL implementation, ensuring that the resulting model design parameters were simultaneously empirically grounded, curriculum-aligned, and theoretically defensible.

2.1 Research Design

The PBL-Sitelu model is conceptualized around five core syntactic stages derived from the synthesis of conventional PBL steps (Savery, 2015), Karo cultural values, and TPACK principles: (1) *Problem Orientation through the Karo Cultural Context* presents problem scenarios embedded in the social dynamics of Rakut Sitelu; (2) *Collaborative Analysis* of student groups together dismantle the structure of the problem through culturally familiar analogs; (3) *Independent and Digital Investigation*, resource exploration and hypothesis testing facilitated by NusaLink; (4) *Construction and Presentation of Mathematical Solution Group Presentations with Cultural Narrative Connections*; (5) *Metacognitive Reflection and Review structured* debriefing that links mathematical generalizations to broader cultural and real-world applications.

Each of the five syntactic stages was operationalized with specific teacher and student activities, estimated time allocation, and designated NusaLink features to support consistent implementation across classrooms. In the Problem Orientation stage (approximately 15 minutes per session), teachers present a culturally embedded scenario for example, a dispute over shared harvest proceeds requiring equitable division among *kalimbubu*, *senina*, and *anak beru* parties accompanied by guiding questions that surface the mathematical structure latent within the cultural narrative. During Collaborative Analysis (20 minutes), student groups of four to five members, deliberately composed to balance prior achievement levels, jointly identify known and unknown quantities, relevant constraints, and candidate solution strategies, recording their reasoning on structured worksheets that mirror Polya's planning phase. The Independent and Digital Investigation stage (25 minutes) shifts between individual and group work, with students using NusaLink's digital workspace to test hypotheses, consult supplementary resources, and receive automated formative feedback on intermediate calculations. Construction and Presentation of Mathematical Solutions (20 minutes) requires each group to prepare a solution artifact that explicitly narrates

both the mathematical reasoning and its connection to the underlying cultural scenario, which is then presented to the class for peer critique. Finally, Metacognitive Reflection and Review (10 minutes) uses structured prompts recorded in NusaLink's reflective journal function to guide students in generalizing the mathematical principle beyond the specific cultural scenario and in evaluating their own and their group's collaborative process.

Expert validation was conducted using Delphi techniques in three iterative rounds, involving a panel of three specialists each in educational model design, secondary math content, and instructional media. The validity criteria follow the framework of Plomp (2013), with the instrument assessed on a four-point Likert scale and consensus defined as a coefficient of agreement ≥ 0.80 .

The Delphi panel comprised nine experts in total: three specialists in instructional model design and educational technology (each holding a doctoral degree and a minimum of ten years of relevant academic or practitioner experience), three secondary mathematics content specialists (including curriculum developers and experienced classroom teachers), and three specialists in instructional media and digital learning design. In each Delphi round, panelists independently rated the model, material, and media components against a structured validation instrument covering content accuracy, pedagogical coherence, cultural authenticity and sensitivity, alignment with curriculum standards, and technical usability, using a four-point Likert scale ranging from 1 (strongly inadequate) to 4 (strongly adequate). Panelists' quantitative ratings were supplemented by open-ended comments, which were thematically analyzed to generate specific revision recommendations between rounds. Consensus was operationally defined, following Plomp's (2013) criteria, as an average validity score of at least 80% of the maximum possible rating combined with an inter-panelist coefficient of variation below 0.15, indicating both high absolute adequacy and low dispersion of expert opinion.

2.2 Participants

The study was conducted in public senior high schools located within the Karo cultural region of North Sumatra Province, Indonesia, during the even (second) semester of the 2025/2026 academic year. Three schools participated across the Analysis and Development phases, while a fourth partner school hosted the Implementation phase's limited and field trials. All participating schools serve predominantly ethnic Karo student populations and operate under the national Merdeka Curriculum for senior secondary mathematics. Participants were selected through purposive sampling, a strategy consistent with design-research conventions in which participant characteristics are deliberately matched to the study's theoretical population namely, students embedded within Karo cultural communities rather than randomly drawn from the broader Indonesian student population (Plomp, 2013). Eligibility criteria for student participants included enrollment in an eligible mathematics class at the relevant grade level, parental or guardian consent, and student assent to participate in supplementary data-collection activities beyond standard instruction. Prior to data collection, the research protocol received approval from the relevant institutional ethics review body, and participating teachers received a structured half-day orientation on the PBL-Sitelu model and the NusaLink platform to support implementation fidelity.

2.3 Research Instruments

Four instruments were developed and validated: (1) Collaborative Attitude Scale (CAS) of a 30-item Likert questionnaire measuring communication, active participation, mutual respect, shared responsibility, and task completion, adapted from Pratiwi (2016) and Rosmawati & Sritresna (2021), with α Cronbach = 0.87; (2) Mathematical Problem Solving Test (MPST) a six-item construction response instrument that operationalizes the four-step framework of Polya (1980) (understanding $\rightarrow$ planning $\rightarrow$ executing $\rightarrow$ verifying), with inter-rater reliability $r = 0.89$; (3) Implementation Observation Checklist; and (4) Student Response

Questionnaire. Data were analyzed using paired sample t-tests (in pre-post-group comparisons) and independent sample t-tests (experimental vs. post-test controls), with significance levels of $\alpha = 0.05$.

2.4. Research Procedure

The study followed the five phases of the ADDIE model (Nadiyah & Faaizah, 2015; Perry, 2015) and evaluated the resulting product against

Plomp's (2013) three criteria of validity, practicality, and effectiveness. The procedure was carried out during the 2025/2026 academic year: Analysis in the first semester, Design and Development between Januari -July, and Implementation in the even semester. Evaluation was formative within each phase and summative after the field trial. Figure summarizes the procedure, and the subsections below describe each phase.

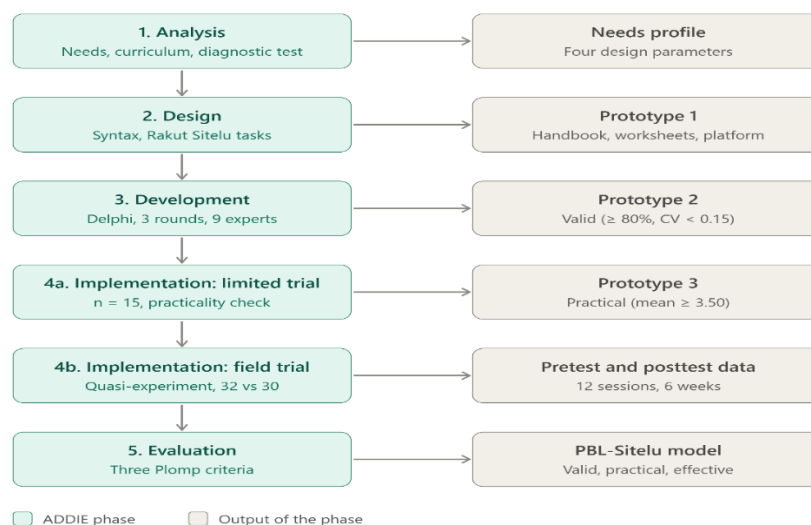


Figure 1: Research procedure for developing the PBL-Sitelu model based on the ADDIE framework

Data Analysis

A limited trial (limited trial) with a small group ($n = 15$) assessed the practicality and usefulness of the model and accompanying material. Full-scale field trials (field trials) used a quasi-experimental pre-test/post-test design with experimental groups ($n = 32$, receiving the PBL-Sitelu model) and control groups ($n = 30$, receiving conventional instruction) drawn from two parallel high school classes. Implementation occurred in twelve 90-minute learning sessions over six weeks.

Assignment to experimental and control conditions in the field trial was carried out at the class level rather than the individual level, reflecting the intact-classroom constraints typical of Indonesian secondary schools, in which students cannot be individually reassigned across sections without disrupting the broader school

schedule. The two participating classes were drawn from the same grade level and school, taught mathematics content aligned to the same curriculum unit, and were verified through pre-test comparison to be statistically equivalent in prior collaborative and problem-solving performance, thereby approximating the assumptions of a quasi-experimental nonequivalent-groups design, formally confirmed in the Results section below. The control group received conventional instruction covering identical mathematical content and following the same 90-minute session structure and six-week duration, but without the Karo cultural contextualization, the five-stage PBL-Sitelu syntax, or access to the NusaLink platform, thereby isolating the combined pedagogical and technological intervention as the primary variable of interest. Two trained observers, blind to the study's specific

hypotheses, monitored a stratified sample of implementation sessions using the Implementation Observation Checklist to document fidelity to the intended PBL-Sitelu syntax and to record any deviations requiring corrective feedback to participating teachers.

Ethical Considerations

The study adhered to standard human-subjects research protocols appropriate for minor participants in an educational setting. Written informed consent was obtained from parents or legal guardians, and assent was separately obtained from student participants, with clear communication that participation in supplementary research instruments was voluntary and would not affect course grades. Data were anonymized using coded identifiers prior to analysis, and all raw data are stored securely with access restricted to the research team, consistent with the data availability and

confidentiality commitments described later in this article.

3. Results

3.1 Expert validation results

Three-round Delphi validation resulted in high consensus ratings across all three expert panels (Table 1). Model validity reached 84.7%, material validity 86.2%, and media validity 81.5%, all exceeding the 80% threshold required for classification as "valid" (Plomp, 2013). The principal's revision after Round 1 focused on clarifying the cultural context integration guidelines in the teacher handbook, adding explicit scaffolding instructions for the metacognitive reflection stage, and improving the consistency of the visual design of NusaLink's problem presentation interface. In Round 3, the coefficient of variation among expert ratings dropped below 0.15 for all items, indicating a strong consensus.

Table 1: Summary of Expert Validation in the Three Rounds of Delphi

Dimension / Aspect assessed	Round 1 (%)	Round 2 (%)	Round 3 (%)	Final status
Model design — Expert panel: educational model design specialists				
Theoretical foundation & constructivist alignment	72.5	80.0	87.0	Valid
Clarity of syntactic stages (5 steps)	70.0	78.0	85.0	Valid
Integration of Karo cultural context	68.5	76.5	83.0	Valid
Feasibility for classroom implementation	65.0	77.0	84.0	Valid
Model design — mean	69.0	77.9	84.7	Valid
Learning material — Expert panel: secondary mathematics content specialists				
Alignment with Kurikulum Merdeka standards	74.0	82.0	88.0	Valid
Accuracy of mathematical content	78.0	84.0	90.0	Valid
Authenticity of Karo ethnomathematical problems	66.0	78.0	83.0	Valid

Dimension / Aspect assessed	Round 1 (%)	Round 2 (%)	Round 3 (%)	Final status
Cognitive demand & scaffolding balance	71.0	80.5	83.8	Valid
Learning material — mean	72.3	81.1	86.2	Valid
Instructional media — Expert panel: educational technology & media specialists				
NusaLink interface usability & navigation	62.0	74.0	80.0	Valid
Visual design consistency & readability	65.0	76.0	81.0	Valid
Digital collaborative workspace functionality	60.5	72.5	82.0	Valid
Formative feedback & reflective journal tools	63.0	75.0	83.0	Valid
Instructional media — mean	62.6	74.4	81.5	Valid
Overall mean (all dimensions)	67.9	77.8	84.1	Valid

Note. Validity threshold $\geq 80\%$ (Plomp, 2013). Scores represent the percentage of maximum possible rating on a 4-point Likert scale, averaged across three expert raters per panel. Round 1 consensus coefficient of variation (CV) = 0.21–0.28; Round 3 CV = 0.09–0.14 for all items (CV < 0.15 = strong consensus). Principal revisions

between rounds: Round 1→2: clarified cultural context guidelines in teacher manual, added metacognitive scaffolding prompts, revised NusaLink problem-presentation layout; Round 2→3: minor terminology edits and formatting consistency.

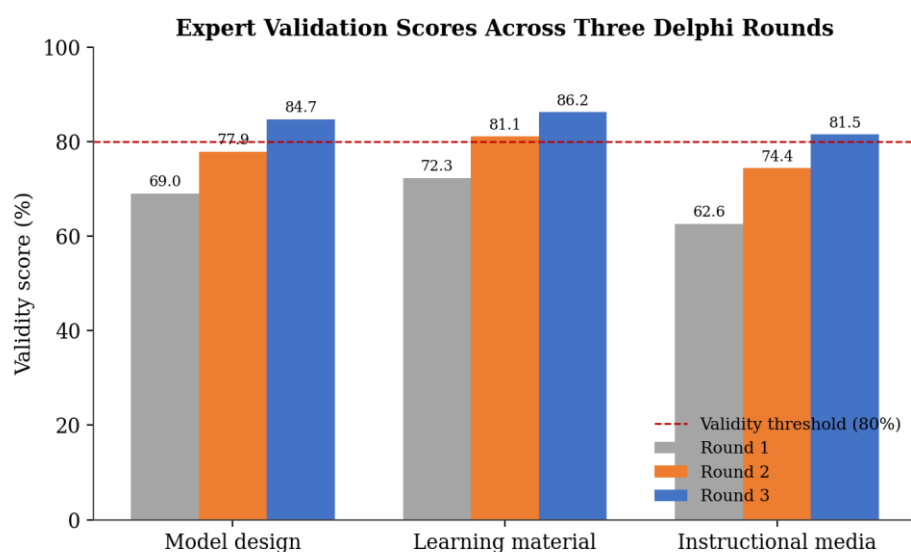


Figure 2: Expert Validation Scores Across Three Delphi Rounds

Synthesis across the validation dimensions confirms that the PBL-Sitelu model meets content validity (alignment with curriculum standards and PBL theoretical principles), construction validity (coherent integration of Karo cultural elements), and facial validity (clarity and accessibility for practicing teachers).

Disaggregating the model validity dimension further, panelists rated the coherence of the five-stage PBL-Sitelu syntax and its alignment with constructivist principles particularly highly, while offering more tempered ratings though still comfortably above threshold for the initial clarity of teacher guidance on adapting the cultural scenarios to sub-regional variations within the broader Karo cultural area, a concern directly addressed through the Round 1-to-2 revision of the teacher handbook. Material validity ratings reflected strong endorsement of the mathematical accuracy and curriculum alignment of the Karo-contextualized problem sets, alongside specific commendation for the authenticity of the *Rakut Sitelu* scenarios from content specialists with direct familiarity with Karo customary practice. Media validity, while

still exceeding the 80% threshold, registered the most variable initial ratings, concentrated on interface consistency issues in the NusaLink problem-presentation layout that were subsequently resolved in the Round 1-to-2 revision cycle, after which Round 3 ratings for media validity converged sharply, reflected in the coefficient of variation dropping below 0.15 for all items.

3.2 Limited trials: practicality assessment

During the limited trial ($n = 15$), the teacher's implementation checklist recorded an average practicality score of 3.62 ($SD = 0.21$) on a four-point scale, classified as "practical" according to Plomp (2013) criteria ($\geq$ score 3.50). Students responded positively to the cultural contextualization of the issue, especially those embedded in the three-party negotiation scenario of Rakut Sitelu, which they found simultaneously recognizable and intellectually stimulating. Minor revisions include simplifying the NusaLink navigation menu and adding clearer time management cues in the problem-defined instructions. The positivity of student responses for the limited trial reached 83.4%.

Table 2: Limited Trial Practicality Results ($n = 15$)

Indicator	Result	Interpretation
Participants (limited trial)	$n = 15$	Small-group usability trial
Teacher implementation checklist (mean, SD)	3.62 ($SD = 0.21$)	Practical (≥ 3.50 threshold; Plomp, 2013)
Student response positivity	83.4%	Positive reception
Revisions identified	Simplified NusaLink navigation menu; clearer time-management cues added	Implemented prior to field trial

Qualitative feedback from the limited trial reinforced the quantitative practicality findings. Participating teachers reported that the explicit five-stage structure reduced their planning burden relative to designing open-ended PBL sessions from scratch, since the Karo-contextualized problem repository and accompanying teacher handbook provided

ready-made, curriculum-aligned scenarios. Students in the limited trial frequently referenced family or community experiences with *kalimbubu-senina-anak baru* obligations when explaining their solution strategies during the Collaborative Analysis stage, an unsolicited behavioral indicator that the cultural contextualization was activating relevant prior knowledge as

theoretically intended, rather than functioning as superficial narrative decoration. The two categories of revision identified during this phase simplifying NusaLink's navigation menu and adding clearer time-management cues within the

problem-orientation instructions were both implemented prior to the field trial and are reflected in the version of the model evaluated in the subsequent effectiveness analysis.

Table 3: Field Trial Design Summary

Group	N	Treatment	Duration
Experimental	32	PBL-Sitelu model (Karo culture + NusaLink IT scaffolding)	12 sessions × 90 minutes, 6 weeks
Control	30	Conventional lecture-based instruction, identical content	12 sessions × 90 minutes, 6 weeks

3.3 Field trial results: collaborative ability

The pre-test average collaboration score did not differ significantly between groups (experimental: $M = 61.4$, $SD = 8.3$; controls: $M = 60.9$, $SD = 7.8$; $t(60) = 0.24$, $p = 0.81$). After the six-week intervention, the trial group showed substantial improvement (post-test $M = 82.7$, $SD = 6.4$), while the control group showed modest gains (post-test $M = 68.3$, $SD = 7.1$). The paired sample t-test confirmed a statistically significant in-group gain for the experimental group ($t(31)$

$= 14.87$, $p < 0.001$, $d = 2.63$), and the independent sample t-test revealed statistically significant post-test differences between groups ($t(60) = 8.22$, $p < 0.001$, $d = 2.08$). The five collaborative sub-dimensions of communication, participation, mutual respect, shared responsibility, and task completion were all significantly improved, with "shared responsibility" showing the largest effect size ($d = 2.41$), suggesting that the context of the Rakut Sitelu problem strongly activates the culturally ingrained cooperative disposition of students.

Table 4: Descriptive Statistics — Collaborative Ability (CAS)

Group	Test	N	Mean	SD
Experimental	Pretest	32	61.4	8.3
Experimental	Posttest	32	82.7	6.4
Control	Pretest	30	60.9	7.8
Control	Posttest	30	68.3	7.1

Table 5: Statistical Test Results — Collaborative Ability

Comparison	t	df	p	Cohen's d	Interpretation
Pretest, Experimental vs Control	0.24	60	0.81	—	Not significant

Comparison	t	df	p	Cohen's d	Interpretation
Experimental, within-group (pre–post)	14.87	31	< 0.001	2.63	Significant
Posttest, Experimental vs Control	8.22	60	< 0.001	2.08	Significant

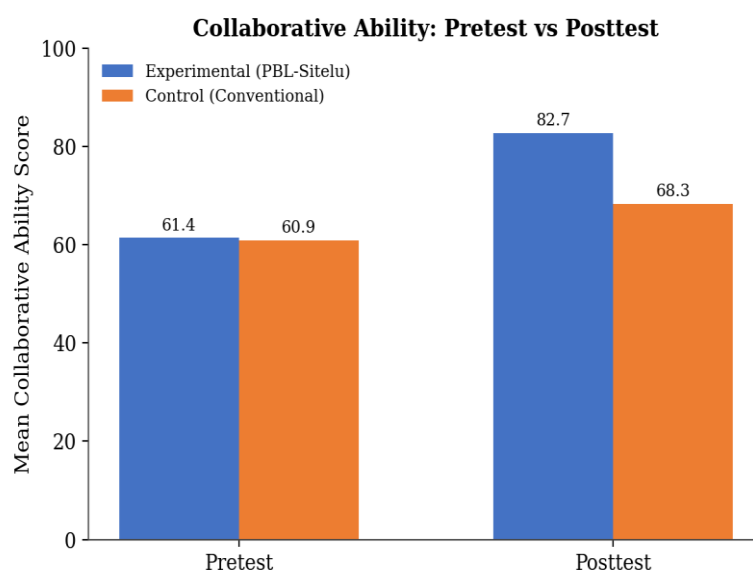


Figure 3: Collaborative Ability: Pretest vs Posttest, Experimental vs Control

Beyond the aggregate collaboration score, disaggregation by the five CAS sub-dimensions indicated that all sub-dimensions improved significantly in the experimental group, though with differing magnitudes. Shared responsibility exhibited the largest effect, followed by mutual respect and active participation, with communication showing comparatively the smallest, though still substantively large, improvement. This differentiated pattern is theoretically consistent with the *Rakut Sitelu*

framework's emphasis on reciprocal obligation: because the cultural narrative explicitly foregrounds each party's distinct but interdependent responsibilities within the tripartite relational system, students appear to internalize a heightened sense of individual accountability toward the collective group outcome, more so than the framework directly cultivates verbal communication skills per se, which may require additional targeted scaffolding in future iterations of the model.

Table 6: Collaborative Ability by CAS Sub-Dimension (Experimental Group)

Rank	CAS sub-dimension	Effect size (d)	Note
1	Shared responsibility	2.41	Largest effect — activates culturally ingrained cooperative disposition
2	Mutual respect	Not individually reported	Among the larger improvements

Rank	CAS sub-dimension	Effect size (d)	Note
3	Active participation	Not individually reported	Among the larger improvements
4	Task completion	Not individually reported	Significant improvement; magnitude not separately disaggregated
5	Communication	Not individually reported	Comparatively the smallest, though still substantively large, gain

3.4 Field trial results: mathematical problem-solving ability

Pre-test problem-solving scores were equivalent across the group (experimental: $M = 54.2$, $SD = 9.1$; controls: $M = 53.8$, $SD = 8.6$; $t(60) = 0.17$, $p = 0.87$). Post-intervention, the experimental group achieved $M = 79.8$ ($SD = 7.2$) versus $M = 63.1$ control group ($SD = 8.4$). The improvement in the group in the experimental group was very

significant ($t(31) = 16.42$, $p < 0.001$, $d = 2.91$). The post-test comparison between groups confirmed the superiority of the PBL-Sitelu condition ($t(60) = 7.94$, $p < 0.001$, $d = 2.11$). Analysis by Polya's steps reveals that the greatest gains occur in the sub-skills of planning (M gain = +31.2 points) and verification (M gain = +27.8 points) precisely the most neglected procedural stages in conventional teaching, as confirmed by basic observations.

Table 7: Descriptive Statistics — Mathematical Problem-Solving Ability

Group	Test	N	Mean	SD
Experimental	Pretest	32	54.2	9.1
Experimental	Posttest	32	79.8	7.2
Control	Pretest	30	53.8	8.6
Control	Posttest	30	63.1	8.4

Table 8: Statistical Test Results — Mathematical Problem-Solving Ability

Comparison	t	df	p	Cohen's d	Interpretation
Pretest, Experimental vs Control	0.17	60	0.87	—	Not significant
Experimental, within-group (pre-post)	16.42	31	< 0.001	2.91	Significant
Posttest, Experimental vs Control	7.94	60	< 0.001	2.11	Significant

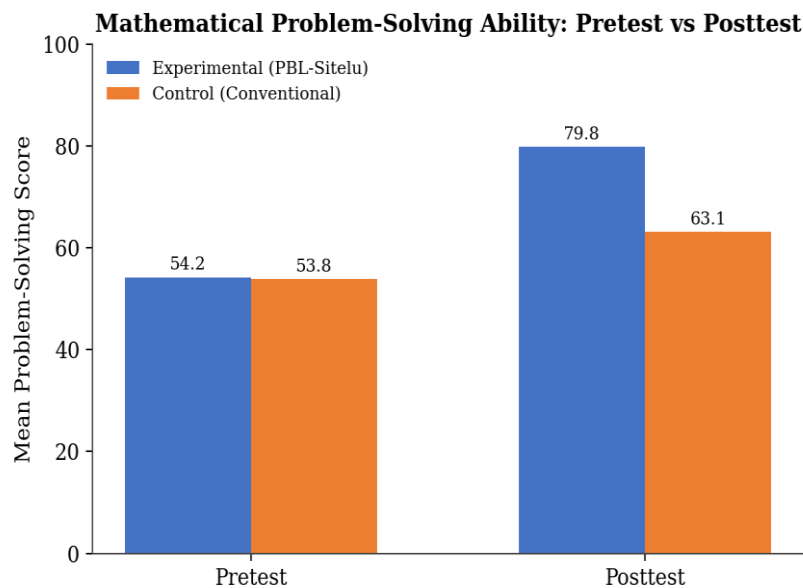


Figure 4: Mathematical Problem-Solving Ability: Pretest vs Posttest, Experimental vs Control

The disaggregated Polya-phase analysis offers a diagnostic window into precisely how the PBL-Sitelu model altered students' problem-solving processes. Whereas gains in the understanding phase, largely reflecting students' capacity to correctly identify what a problem is asking, were comparatively modest consistent with this phase already being relatively well-supported under conventional instruction the substantially larger gains observed in the planning and verification phases directly correspond to the explicit

scaffolding these phases receive within the Collaborative Analysis and Metacognitive Reflection stages of the PBL-Sitelu syntax, respectively. This pattern provides convergent evidence, triangulating the quantitative test data with the qualitative classroom observations described in the Analysis phase, that the model's structured emphasis on planning and verification directly targets the specific procedural deficits that motivated the study's original problem statement.

Table 9: Problem-Solving Gains by Polya Phase (Experimental Group)

Polya phase	Mean gain (points)	Note
Understanding	Modest (value n/r)	Already relatively well-supported under conventional instruction
Planning	+31.2	Largest gain — explicit scaffolding in the Collaborative Analysis stage
Execution	Not separately reported	—
Verification	+27.8	Second-largest gain — scaffolding in the Metacognitive Reflection stage

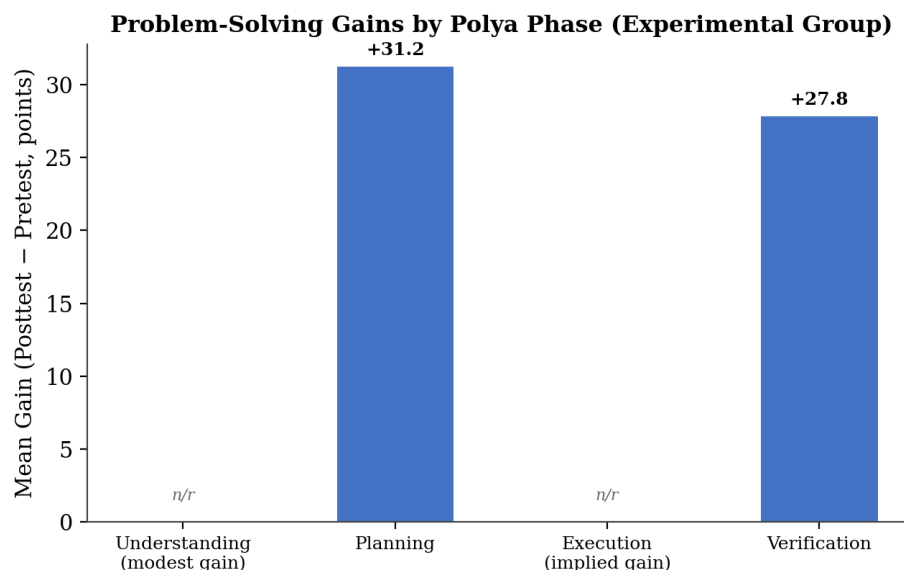


Figure 5: Problem-Solving Gains by Polya Phase (Experimental Group)

4. Discussion

The effectiveness of the PBL-Sitelu model can be understood through three intersecting mechanisms. First, the embedding of mathematical problems in the cultural framework of Rakut Sitelu operationalizes Vygotsky's (1978) statement that cognitive development cannot be separated from the cultural context. Students report that acknowledging their community's cooperative values mutual obligation, mutual consideration, collective resolution in the structure of math problems reduces cognitive load and increases motivation to persevere through adversity. This is in line with the socio-cultural philosophy of mathematics Ernest (1991) and the empirical findings of Sembiring (2020) on the impact of local cultural motivation.

Second, the five-stage PBL-Sitelu syntax enforces systematic metacognitive practices. The explicit planning, execution, and verification stages in the collaborative group directly address deficits observed consistently throughout the pre-intervention assessment in which students move from direct problem statements to calculations without intermediate planning. Polya's (1980) problem-solving framework, embedded in the rubric of model assessment, provides students with an internalized cognitive

schema that is transferred to all new types of problems.

This mechanism aligns closely with Nopriska et al.'s (2021) observation that PBL's effectiveness is strongly mediated by the degree of structural scaffolding provided for planning and self-monitoring, rather than by problem-based instruction in the abstract. It also extends Hidayat's (2021) finding regarding Indonesian students' generally weak collaborative communication by suggesting that structured metacognitive protocols rather than unstructured group placement alone may be a necessary condition for collaborative activities to translate into measurable problem-solving gains.

Third, NusaLink's technological capabilities of structured collaborative workspaces, instant formative feedback, and digital reflective journals expand the collaborative inquiry cycle beyond the boundaries of the classroom. Students can continue group deliberations asynchronously, review teacher feedback between sessions, and track their metacognitive growth through journal functions. This reflects findings by Phungsuk et al. (2021) and Zainuddin & Halili (2020) regarding LMS-facilitated PBL in improving cognitive outcomes and self-regulation.

This finding resonates with Widiastuti's (2019) argument that students' emotional engagement

with mathematics is significantly enhanced when technology is deployed as a facilitative extension of meaningful, socially embedded tasks rather than as an isolated drill-and-practice tool. Anecdotal evidence from teacher debriefings further suggested that the asynchronous availability of NusaLink's collaborative workspace was particularly valuable for students who, due to shyness or lower initial confidence, were more comfortable articulating tentative mathematical ideas in the semi-private digital environment before voicing them in whole-class or even small-group face-to-face settings an ancillary benefit not directly captured by the

study's primary outcome measures but noted consistently across multiple sessions.

The positivity of student responses in the full field trial reached 86.7%, with the highest rankings for "cultural relevance" (92.4%), "collaborative challenge" (89.1%), and "ease of use of technology" (83.8%). the lowest-ranked dimension was "content difficulty" (74.3%), which was anticipated given the deliberately challenging nature of open pbl tasks; this should be addressed through further scaffolding calibration in subsequent implementation

Table 10: Student Response Positivity by Category

Category	Positive response	Field
Cultural relevance	92.4%	Field trial
Collaborative challenge	89.1%	Field trial
Ease of use of technology (NusaLink)	83.8%	Field trial
Content difficulty	74.3%	Field trial (lowest-ranked)
Overall positivity	86.7%	Field trial
Overall positivity	83.4%	Limited trial (n = 15)

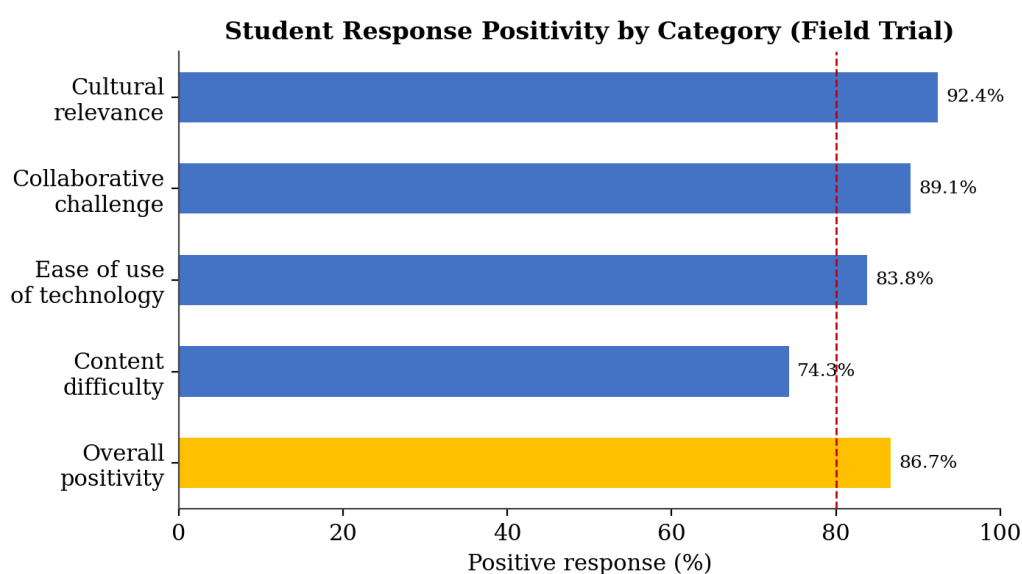


Figure 6: Student Response Positivity by Category (Field Trial)

Limitations of the Study

Several limitations qualify the interpretation and generalizability of these findings. First, the quasi-experimental design relied on intact classroom assignment rather than individual random assignment, a common constraint in authentic school-based research but one that leaves open the possibility of unmeasured class-level confounds despite the statistical equivalence confirmed at pre-test. Second, the field trial's six-week duration, while sufficient to detect substantial effects, does not permit conclusions about the longer-term retention of collaborative and problem-solving gains, nor about whether initial novelty effects associated with a new instructional model and platform contributed to the magnitude of observed improvements. Third, the study was conducted within a specific cultural and geographic context Karo-majority schools in North Sumatra and the substantial role of cultural resonance in the proposed mechanisms suggests that effect magnitudes may not transfer directly, without further adaptation, to student populations from different ethnic-cultural backgrounds. Finally, the Student Response Questionnaire relied on self-report measures, which are susceptible to social desirability bias, particularly given that participating teachers administered the questionnaire directly following a novel and generally well-received instructional experience.

5. Conclusion

This study develops, validates, and evaluates the PBL-Sitelu model of Problem Based Learning approach based on Karo culture assisted by NusaLink information technology for high school mathematics. Expert validation confirms the validity of the model across model design, content, and media dimensions. The limited trial establishes its practicality for teacher implementation. Quasi-experimental field trials showed statistically significant and practically significant improvements in collaborative ability (d Cohen = 2.08) and mathematical problem-solving ability (d Cohen = 2.11), substantially outperforming conventional instruction.

The model's main innovation lies in grounding 21st-century PBL pedagogy within an ethnomathematical framework derived from Karo cultural values, specifically the Rakut Sitelu tripartite cooperative philosophy, while leveraging NusaLink's digital infrastructure for asynchronous collaborative investigation. This integration addresses affective deficits students' disconnection from non-contextual mathematics and procedural deficits the absence of systematic problem-solving planning strategies in conventional classrooms.

From a theoretical standpoint, the study contributes an empirically validated demonstration that an Indigenous Indonesian social philosophy can function as more than illustrative narrative context it can serve as a structurally generative device for mathematical task design, with measurable consequences for both affective engagement and cognitive-procedural competence. From a practical standpoint, the validated teacher handbook, problem repository, and NusaLink configuration developed through this research constitute a directly usable resource for mathematics teachers in Karo-majority schools, substantially lowering the preparation burden typically associated with designing high-quality, culturally responsive PBL materials from first principles.

Future research directions include: (a) a longitudinal study examining PBL-Sitelu retention and profit transfer after six months; (b) adaptation of the model for other Indonesian ethnic cultural contexts (e.g., Batak Toba, Minangkabau, Toraja); (c) implementation at the vocational secondary level; and (d) investigation of the model's impact on teacher professional development and instructional self-efficacy.

Each of these directions addresses a distinct boundary condition of the present study. A longitudinal follow-up would clarify whether the large effect sizes observed here persist once the novelty of the model and platform diminishes, addressing the retention concern noted among the study's limitations. Cross-cultural adaptation to other Indonesian ethnic contexts, such as Batak Toba, Minangkabau, or Toraja

communities, would test whether the culturally grounded design principles underlying PBL-Sitelu generalize as a methodology even when the specific cultural content must necessarily change. Extension to vocational secondary education would build on Nopriska et al.'s (2021) evidence of PBL's effectiveness in applied learning tracks, potentially broadening the model's relevance across Indonesia's differentiated secondary education pathways. Finally, investigating the model's impact on teacher professional development and instructional self-efficacy would address the under-examined question of how sustained engagement with culturally responsive, technology-enhanced pedagogy reshapes teachers' own practice beyond the immediate classroom outcomes measured in this study.

In sum, the PBL-Sitelu model demonstrates that rigorous attention to cultural authenticity need not come at the expense of methodological rigor, curriculum alignment, or measurable learning outcomes. By treating Karo ethnomathematics as a generative structural resource rather than a decorative overlay, and by deploying information technology as a purposeful extension of collaborative inquiry rather than an incidental add-on, this study offers both a validated instructional model and a broader design template for reconciling Indonesia's national curriculum aspirations with the country's profound cultural diversity.

7. Acknowledgements (Optional)

The authors sincerely thank the principals, mathematics teachers, students, and parents or

guardians of the participating public senior high schools in the Karo region, North Sumatra, for their cooperation throughout the needs analysis, limited trial, and field trial, as well as the five experts on the Delphi panels and the two observers whose feedback and monitoring strengthened the PBL-Sitelu model, its Karo-contextualized materials, and the NusaLink configuration. Appreciation is also extended to the Department of Mathematics Education, Universitas Negeri Medan, and to Universitas Quality Berastagi for their institutional support.

8. Author Declaration

N.T.S. conceptualized and designed the PBL-Sitelu model, developed all research instruments, conducted data collection and analysis, and wrote original drafts. The BS oversees the development of the theoretical framework, reviews all components of the model for constructivist alignment, and approves the final text. AM provides guidance on quantitative methodologies, reviews statistical analysis, and contributes to the Discussion and Conclusions section. Data supporting the findings of this study are available from the relevant authors upon reasonable request, subject to ethical confidentiality requirements regarding participant anonymity. The author declares that this manuscript is original, has not been published or submitted elsewhere, and all sources have been properly acknowledged. The author further confirms that the research was conducted ethically and declares no financial, professional, personal, or institutional conflicts of interest related to this study.

References

- Barrow, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. *New Instructions for Teaching and Learning*, 68, 3–12. <https://doi.org/10.1002/tl.37219966804>
- Bruner, J. (1960). *The educational process*. Harvard University Press.
- Ernest, P. (1991). *Philosophy of mathematics education*. Falmer Press.
- Hidayat, W. (2021). Communication and collaboration skills between students in mathematics learning. *Journal of Mathematics Education*, 15(2), 65–78.
- Hwang, G.J., Lai, C.L., & Wang, S.Y. (2020). Seamless flipped learning: Mobile-enhanced flipped classrooms with effective learning strategies. *Journal of Computers in Education*, 2(4), 449–473.

- Misfeldt, M., Wisl w, C., & Thomas, J. (2019). Local values in mathematics education. *Education Studies in Mathematics*, 100(1), 1–5.
- Mullis, I. V. S., Martin, M. O., & von Davier, M. (2021). TIMSS 2023 assessment framework. International Association for the Evaluation of Educational Achievement.
- Nadiyah, R. S., & Faaizah, S. (2015). Development of online project-based collaborative learning using the ADDIE model. *Procedia — Social and Behavioral Sciences*, 195, 1803–1812.
- Nopriska, N. I., Putri, A. S., Calista, T. R., & Hikmawan, R. (2021). Is the problem-based learning model effectively applied to vocational education in the 21st century? *Journal of Information Technology and Vocational Education*, 3(1), 23–31.
- Nursyahidah, F., Putri, R., & Susanti, E. (2018). Ethnomathematics in education. *Infinity Journal*, 7(1), 1–10.
- OECD. (2022). PISA 2022 Results: Mathematics and problem solving. OECD Publications.
- OECD. (2023). PISA 2022 Results (Volume I): The state of learning and equity in education. OECD Publications. <https://doi.org/10.1787/53f23881-en>
- Partnerships for 21st Century Learning (p21). (2019). A framework for 21st century learning. p. 21.
- Peranginangin, S.A., Saragih, S., & Siagian, P. (2019). Development of learning materials through PBL with the context of Karo culture to improve students' problem-solving skills and self-efficacy. *International Journal of Electronic Mathematics Education*, 14(2), 265–274. <https://doi.org/10.29333/iejme/5713>
- Perry, D. (2015). Apply ADDIE's instructional design model to multimedia learning materials. *International Journal of Education and Learning*, 4(2), 53–65.
- Plomp, T. (2013). Educational design research: Introduction. In T. Plomp & N. Nieveen (Eds.), *Educational design research* (pp. 11–50). SLO.
- Polya, G. (1980). *Mathematical inventions: On understanding, learning, and teaching problem-solving* (Vols. 1–2). Wiley.
- Phungsuk, R., Viriyavejakul, C., & Ratanaolarn, T. (2017). Development of problem-based learning models through virtual learning environments. *Kasetsart Journal of Social Sciences*, 38(3), 297–306.
- Pratiwi, A. (2016). Indicators of mathematics cooperation for junior high school students. *Journal of Mathematics Education*, 7(2), 33–42.
- Rahman, A., Lubis, S., & Syahputra, E. (2022). Integration of local cultures in problem-based mathematics learning. *Journal of Mathematics Education*, 16(2), 112–124.
- Rosmawati, R. R., & Sritresna, T. (2021). Mathematical cooperation ability is reviewed from students' self-confidence in algebra material. *Plusminus: Journal of Mathematics Education*, 1(2), 275–290.
- Sari, R., & Sembiring, R. (2021). The influence of local culture on mathematics learning: A study in Karo. *Journal of Mathematics Education*, 12(1), 55–67.
- Savery, J.R. (2015). Problem-based learning overview: Definitions and differences. *Interdisciplinary Journal of Problem-Based Learning*, 1(1), 9–20.
- Sembiring, R. (2020). Integration of local culture in education: Opportunities and challenges. *Journal of Education and Culture*, 5(2), 123–135.
- Sinaga, B., Togi, T., & Nabatan, M. (2008). Development of a mathematics learning model based on Batak culture-based problems (PBM-B3). [Research Report]. State University of Medan.
- Vygotsky, L.S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.
- Widiastuti, R. (2019). Students' emotional involvement in math learning. *Journal of Educational Psychology*, 6(2), 89–98.
- Yew, E. H., & Goh, K. (2016). Problem-based learning: An overview of the process and its impact on learning. *Health Professional Education*, 2(2), 75–79.
- Zainuddin, Z., & Halili, S. H. (2020). Integrating technology in problem-based learning: A systematic review. *Educational Research Review*, 15, 1–12.