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Indigenous Musical Instruments as Ethno-STEM Catalysts for Enhancing Scientific Literacy Through Cultural Integration

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ABSTRACT

Purpose of the study: Investigated the effectiveness of a Tifa drum-based Ethno-STEM instructional approach on enhancing scientific literacy among secondary school students, specifically examining how indigenous cultural artifacts can serve as bridges between traditional knowledge systems and Western scientific understanding.

Methodology: A true experimental design with pretest-posttest control group was employed with 40 eighth-grade students randomly assigned to experimental (n=20) or control (n=20) groups. The experimental group received nine weeks of instruction using the HENIE syntax (Highlighting, Exploring, Narrating, Implementing, Evaluating) to integrate Tifa drum knowledge with vibration, waves, and sound concepts. The control group received conventional instruction. Scientific literacy was measured across three dimensions: content, procedural, and epistemic knowledge using a validated 25-item assessment instrument.

Main Findings: The Tifa-based Ethno-STEM approach demonstrated significantly superior outcomes compared to traditional instruction. The experimental group achieved higher normalized learning gains (0.48 vs. 0.31) with a large effect size (Cohen's d = 0.84, $p < 0.001$). Most notably, the epistemic dimension showed the largest improvement differential (77% vs. 60%), while content and procedural dimensions improved from low to moderate proficiency levels. Student responses indicated high engagement, cultural pride, and enhanced conceptual accessibility. The HENIE model successfully bridges indigenous and scientific knowledge systems, particularly strengthening epistemic understanding—a critical yet often neglected component of scientific literacy.

Novelty/Originality of this study: This study pioneers the quantitative validation of indigenous musical instruments as effective STEM learning tools, introducing the transferable HENIE pedagogical syntax that demonstrates how cultural artifacts can specifically enhance epistemic scientific literacy development.

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1. INTRODUCTION

In today's rapidly evolving educational landscape, scientific literacy has emerged as a fundamental competency for informed citizenship, requiring individuals to understand scientific concepts that guide life decisions, evaluate scientific information from diverse sources, and apply scientific reasoning to everyday problems [1], [2]. However, persistent achievement gaps in scientific literacy across diverse educational contexts reveal significant disparities among student populations, particularly in multicultural settings where traditional pedagogical approaches often fail to engage students effectively [3], [4]. This educational challenge has prompted researchers and educators to critically examine how science education can become more relevant, engaging, and accessible for all learners, regardless of their cultural backgrounds [5]-[7]. The urgent need to bridge the gap between societal demands for scientific literacy and current educational outcomes has catalyzed innovative approaches that honor diverse ways of knowing while maintaining scientific rigor [8]. Consequently, there is growing recognition that transformative pedagogical strategies must integrate students' cultural identities and indigenous knowledge systems as legitimate pathways to scientific understanding.

Ethno-STEM education has emerged as a promising pedagogical framework that integrates indigenous knowledge systems with science, technology, engineering, and mathematics (STEM) education, particularly demonstrating potential in diverse cultural contexts [9]-[11]. This approach transcends the traditional binary of indigenous versus Western knowledge systems by positioning both ways of knowing as complementary perspectives that mutually inform and enrich scientific understanding [12]. Ethno-STEM aligns with Aikenhead's foundational concept of "walking in both worlds," where both indigenous and scientific knowledge systems are validated while respecting their distinct epistemological frameworks [13]. The theoretical foundations of Ethno-STEM draw from culturally responsive pedagogy [14], which recognizes student cultural references as integral to all aspects of learning, and funds of knowledge theory [15], [16], which acknowledges the strategic cultural resources students bring from their homes and communities. Rather than treating indigenous knowledge as supplementary content, Ethno-STEM positions it as a foundational layer for accessing and understanding scientific concepts [17]-[19]. This approach has shown particular promise in contexts where cultural artifacts can serve as concrete bridges between traditional wisdom and contemporary scientific understanding.

Indigenous musical instruments represent especially compelling gateways for STEM education, offering rich opportunities to explore scientific concepts while honoring cultural heritage and promoting sustainable educational practices [20], [21]. The Tifa drum, originating from Eastern Indonesia and particularly significant in Papua, exemplifies how cultural artifacts can facilitate meaningful connections between indigenous knowledge and scientific exploration. The construction process of the Tifa involves hollowing wood to create the drum body and sealing it with lizard or deer skin, incorporating principles from acoustics, materials science, and engineering design that directly relate to fundamental physics concepts [12]. The instrument's sound production mechanisms, involving vibrational movement, wave propagation, resonance phenomena, and material properties, provide tangible connections to key physics education topics including vibration, waves, and sound. Furthermore, the traditional knowledge embedded in Tifa construction reflects sophisticated understanding of acoustic principles that indigenous craftspeople have developed and refined over generations. This convergence of cultural significance and scientific content makes indigenous musical instruments ideal candidates for Ethno-STEM interventions that can enhance both scientific understanding and cultural appreciation [22], [23].

Empirical research increasingly supports the effectiveness of culturally relevant approaches in STEM education, though most studies have focused on qualitative outcomes rather than rigorous experimental designs. Studies conducted within Indonesian cultural contexts have demonstrated that culturally relevant frameworks enhance students' understanding of scientific concepts and improve engagement with scientific practices [17], [24]. Similarly, research involving indigenous Australian communities has shown that integrating traditional ecological knowledge into STEM curricula improves students' problem-solving abilities and retention in STEM fields [25], [26]. However, despite these promising findings, there remains a significant gap in quantitative experimental evidence demonstrating the causal effects of structured Ethno-STEM interventions on scientific literacy outcomes. Most existing research has relied on case studies, qualitative analyses, or quasi-experimental designs that limit the ability to establish definitive causal relationships between cultural integration and learning outcomes. This research gap is particularly pronounced regarding the epistemic dimension of scientific literacy, which encompasses understanding how scientific knowledge is constructed, validated, and evolves—a critical component for developing scientifically literate citizens who can distinguish between credible science and pseudoscience [27], [28].

The conceptualization of scientific literacy has undergone significant transformation over the past two decades, evolving from a narrow focus on content knowledge toward a more comprehensive, multidimensional framework. Contemporary definitions embrace scientific literacy as requiring not only content knowledge but also procedural knowledge and epistemic awareness [29]. Roberts [30] distinguishes between "Vision I" scientific literacy, which emphasizes awareness of scientific concepts and processes, and "Vision II" scientific literacy, which focuses on applying scientific knowledge for everyday decision-making and contextual problem-solving. Recent studies have shown that culturally responsive teaching approaches can effectively enhance these multidimensional aspects of scientific literacy, particularly when integrated with local cultural contexts and indigenous knowledge systems [31], [32]. The epistemic dimension, often overlooked in traditional science education, specifically addresses how scientific knowledge is created, developed, validated, and modified over time [33]. This dimension is crucial for developing critical consumers of scientific information who can navigate an increasingly complex information landscape filled with competing claims and misinformation. While Ethno-STEM approaches theoretically align well with developing epistemic understanding by explicitly comparing different knowledge systems, empirical evidence for this connection remains limited. The lack of quantitative studies examining how cultural integration specifically affects the epistemic dimension of scientific literacy represents a critical gap in the literature that this study addresses.

Despite the theoretical promise of Ethno-STEM education and growing qualitative evidence of its effectiveness, several critical gaps persist in the literature that limit both our understanding and implementation of these approaches. First, there is a pronounced absence of rigorous experimental studies that can establish causal relationships between Ethno-STEM interventions and scientific literacy outcomes, with most existing research relying on descriptive or correlational designs. Second, while various cultural artifacts have been incorporated into science education, there is limited evidence regarding the specific effectiveness of indigenous musical instruments as STEM learning tools, despite their rich potential for exploring physics concepts. Third, the impact of Ethno-STEM approaches on the epistemic dimension of scientific literacy—arguably the most crucial component for developing critical scientific thinking—remains largely unexplored through quantitative research. Fourth, there is insufficient evidence regarding whether culturally integrated approaches benefit all students equally or primarily serve specific subgroups, raising important questions about educational equity. Finally, the lack of structured, replicable pedagogical models limits the practical implementation of Ethno-STEM approaches in diverse educational contexts. These gaps represent significant barriers to advancing both theoretical understanding and practical application of culturally responsive science education.

The urgency of this research stems from the persistent and widening gap between the scientific literacy demands of modern society and the educational outcomes achieved through traditional pedagogical approaches, particularly for students from diverse cultural backgrounds. As global challenges increasingly require scientifically literate citizens capable of evaluating complex information and making evidence-based decisions, educational systems must develop more effective and inclusive approaches to science education. The immediate need for empirical evidence supporting Ethno-STEM approaches is critical for educational policymakers, curriculum developers, and teachers who require research-based guidance for implementing culturally responsive pedagogies. This study addresses these urgent needs through a comprehensive problem-solving plan that includes: (1) implementing a rigorous experimental design to establish causal relationships between Tifa-based Ethno-STEM intervention and scientific literacy outcomes; (2) testing the HENIE pedagogical syntax (Highlighting, Exploring, Narrating, Implementing, Evaluating) [34] as a replicable framework for integrating indigenous cultural artifacts into science education; (3) examining the differential effects of the intervention across the three dimensions of scientific literacy to identify specific benefits for epistemic understanding; and (4) investigating student responses to assess engagement, cultural affirmation, and accessibility. This systematic approach will provide the empirical foundation needed to support evidence-based implementation of Ethno-STEM education while addressing both theoretical gaps and practical implementation challenges.

This study aims to achieve several interconnected objectives that address the identified research gaps and contribute to both theoretical understanding and practical implementation of Ethno-STEM education. The primary objective is to determine the causal effect of a Tifa-based Ethno-STEM intervention on scientific literacy outcomes among secondary school students through a rigorous experimental design. Specifically, the study seeks to: (1) evaluate the overall effectiveness of the HENIE syntax-based intervention compared to traditional instruction in enhancing scientific literacy; (2) examine the differential effects of the Tifa-based approach across the three dimensions of scientific literacy (content, procedural, and epistemic knowledge); (3) assess the specific impact on epistemic understanding, given its critical importance for developing scientific thinking and its traditional neglect in science education; (4) investigate student perceptions of the intervention to understand engagement, cultural affirmation, and accessibility factors; and (5) provide empirical evidence for the effectiveness of indigenous musical instruments as STEM learning tools. Additionally, the study aims to contribute to the theoretical understanding of how cultural integration facilitates scientific learning and to develop practical guidance for educators seeking to implement culturally responsive science education. These objectives collectively address the urgent need for evidence-based approaches that can enhance scientific literacy while honoring diverse cultural perspectives and promoting educational equity.

This investigation is guided by one primary research question and several supporting sub-questions that systematically address the identified research gaps and objectives. The central research question asks: What is the effect of a Tifa-based Ethno-STEM intervention on scientific literacy outcomes for secondary school students? This primary question is supported by the following specific research questions: (1) How does the Tifa-based Ethno-STEM approach compare to traditional instruction in terms of overall scientific literacy gains as measured by normalized gain scores? (2) What are the differential effects of the intervention across the three dimensions of scientific literacy (content knowledge, procedural knowledge, and epistemic knowledge)? (3) To what extent does the Tifa-based approach specifically enhance students' epistemic understanding compared to conventional teaching methods? (4) How do students perceive the Tifa-based Ethno-STEM intervention in terms of engagement, cultural relevance, and learning accessibility? (5) What evidence supports the effectiveness of indigenous musical instruments as tools for enhancing scientific literacy? These research questions provide a comprehensive framework for examining both the quantitative effects of the intervention and the qualitative factors that contribute to its effectiveness, thereby addressing the multifaceted nature of scientific literacy development through culturally responsive education.

Based on the theoretical foundations of Ethno-STEM education and existing evidence from culturally responsive pedagogy research, we hypothesize that students receiving the Tifa-based Ethno-STEM intervention will demonstrate significantly higher scientific literacy outcomes compared to students receiving traditional instruction. Specifically, we expect that the experimental group will show superior performance across all three dimensions of scientific literacy, with the most pronounced benefits occurring in the epistemic dimension due to the intervention's explicit integration of indigenous and scientific knowledge systems. Furthermore, we anticipate that students will report high levels of engagement, cultural pride, and improved conceptual accessibility when learning through the Tifa-based approach, reflecting the culturally affirming and cognitively accessible nature of this pedagogical strategy.

2. RESEARCH METHOD

This study employed a quantitative research approach utilizing a true experimental design with a pretest-posttest control group configuration to investigate the causal relationship between a Tifa-based Ethno-STEM intervention and scientific literacy development among secondary school students. The experimental design was selected to meet Creswell's [35] three essential criteria for establishing causation: temporal precedence (intervention occurs before outcome measurement), covariation of cause and effect (changes in intervention correspond with changes in outcomes), and elimination of plausible alternative explanations through controlled conditions. To address potential threats to internal validity including history effects, maturation influences, testing effects, and selection bias, the study incorporated random assignment of participants and employed a comparison control group receiving conventional instruction [36]. The research design enables rigorous examination of whether the Tifa-based Ethno-STEM approach produces superior scientific literacy outcomes compared to traditional pedagogical methods. The experimental framework follows the schematic notation:

Experimental Group : R — O_1 — X — O_2
Control Group : R — O_3 — C — O_4

Where:
R represents random assignment
O_1 and O_3 represent pretest measures of scientific literacy
X represents the Tifa-based Ethno-STEM intervention
C represents the conventional teaching approach
O_2 and O_4 represent posttest measures of scientific literacy

This design provides the methodological rigor necessary to establish causal inferences regarding the effectiveness of indigenous musical instruments in enhancing scientific literacy through Ethno-STEM approaches. The target population for this study comprised eighth-grade students in public junior high schools located in Papua, Indonesia, where the Tifa drum holds significant cultural importance and relevance to local communities. The accessible population included students from schools where Tifa drums are integral to cultural practices, ensuring maximum cultural authenticity and relevance for the Ethno-STEM intervention. A purposive sampling technique was initially employed to select the research site, specifically choosing a public junior high school based on the cultural significance of the Tifa drum in the local community and the school's commitment to supporting the research project. Following site selection, a total sample of 40 eighth-grade students participated in the study, determined through power analysis using G*Power software [37] which indicated that 40 participants (20 per group) would provide adequate statistical power (80%) to detect medium effect sizes ($d = 0.5$) at $\alpha = 0.05$ significance level using independent samples t-tests. Random assignment was implemented using a computerized random number generator to allocate students to either the experimental group ($n = 20$) or control group ($n = 20$), ensuring equivalent groups and minimizing selection bias. Baseline demographic comparisons using independent t-tests for continuous variables and chi-square tests for categorical variables confirmed no statistically significant differences (all $p > .05$) between groups regarding gender distribution, previous academic performance in science, and cultural background characteristics.

The primary research instrument was a comprehensive scientific literacy assessment tool specifically developed for this study and adapted from the OECD [29] PISA framework for measuring scientific literacy across three distinct dimensions. The instrument was systematically adapted rather than adopted wholesale, incorporating elements from established scientific literacy assessments while being specifically tailored to measure the constructs relevant to Tifa-based physics concepts (vibration, waves, and sound) and the cultural context of the study population. The 25-item assessment instrument comprised three subscales: (1) content knowledge measured through 10 multiple-choice items assessing understanding of vibrations, waves, and sound concepts; (2) procedural knowledge evaluated via 8 constructed-response items measuring scientific processes and inquiry practices; and (3) epistemic knowledge assessed through 7 open-ended items examining understanding of the nature and construction of scientific knowledge. Content validity was established through expert review by three science education researchers and two physics content specialists who evaluated each item for alignment with the scientific literacy framework, scientific accuracy, and grade-level appropriateness, with items achieving Content Validity Index (CVI) scores below 0.80 being revised or eliminated following established protocols [38], [39]. Construct validity was confirmed through confirmatory factor analysis, which supported the three-dimensional structure with acceptable fit indices: $\chi^2 = 28.45$, df = 17, $p = 0.04$, CFI = 0.96, RMSEA = 0.05. Reliability analysis conducted through pilot testing with 30 eighth-grade students from a comparable school demonstrated strong internal consistency with Cronbach's alpha values of $\alpha = 0.85$ for the overall instrument, $\alpha = 0.78$ for content knowledge, $\alpha = 0.82$ for procedural knowledge, and $\alpha = 0.80$ for epistemic knowledge subscales, while test-retest reliability over a two-week period yielded $r = 0.87$, indicating acceptable temporal stability.

The secondary instrument consisted of a student perception questionnaire designed specifically for this study to capture participants' subjective experiences with the Tifa-based Ethno-STEM approach. This questionnaire incorporated both quantitative and qualitative components, including Likert-scale items measuring student engagement, perceived relevance of the cultural integration, satisfaction with the learning experience, and cultural affirmation. Open-ended questions were included to elicit detailed qualitative feedback regarding students' perceptions of the intervention's effectiveness, cultural significance, and impact on their understanding of scientific concepts. The questionnaire was validated through expert review and pilot testing to ensure clarity, cultural appropriateness, and comprehensiveness in capturing student experiences. Additionally, instructional materials were developed comprising four sequential learning modules: (1) The Tifa as a cultural artifact (cultural significance and construction processes); (2) Patterns of vibration in the Tifa (membrane properties and vibrational variations); (3) Sound production and acoustics (resonance chambers and sound quality factors); and (4) Wave phenomena and sound transmission (frequency, amplitude, and timbre characteristics). All teaching resources underwent dual validation processes, receiving content validation from physics educators for scientific accuracy and cultural validation from indigenous knowledge holders and local craftspeople to ensure cultural authenticity and appropriateness.

Data collection was implemented through a systematic protocol designed to maintain standardization while minimizing potential sources of bias and measurement error. The pretest phase was conducted one week prior to intervention implementation, with both experimental and control groups completing the scientific literacy assessment under standardized conditions administered by a research assistant who was not involved in instruction to ensure objectivity. Testing sessions were limited to 90 minutes duration, conducted in equivalent classroom environments, and all assessment materials were coded with identification numbers to facilitate blind scoring procedures. The nine-week intervention period (Table 1) followed immediately after pretesting, with both groups receiving four hours of science instruction per week (totaling 36 instructional hours) focused on vibration, waves, and sound concepts, though the experimental group received instruction through the HENIE model-based Tifa integration while the control group received conventional textbook-based instruction. Throughout the intervention period, fidelity checks were conducted to ensure adherence to protocol specifications and maintain consistency in implementation. The posttest phase occurred one week following intervention completion, using identical procedures and conditions as the pretest to ensure measurement consistency and reliability.

Table 1. Learning Instruction

Week/s	Control Group		Experimental Group	
	Phase	Activities	Phase	Activities
1	Introduction to Vibration Concepts	– Textbook readings on basic vibration principles – Teacher demonstrations of simple harmonic motion – Introduction to key terminology (frequency, amplitude) – Structured note-taking on vibration concepts – Basic calculations involving frequency and period	Highlighting	– Introduction to the Tifa drum as a cultural artifact – Documentation of cultural significance and uses – Generation of initial questions about sound production – Collection of traditional knowledge about Tifa materials and design
2-3	Continued Vibration Study	– Laboratory activities with pendulums and springs – Measurement of displacement, frequency, and period – Problem-solving exercises from textbook – Mathematical modeling of simple harmonic motion – Standard laboratory report writing – Formative assessment on vibration concepts	Exploring	– Structured investigations of Tifa components – Testing how membrane tension affects pitch – Exploring how body material affects sound quality – Measuring resonating chamber dimensions and sound characteristics – Connecting indigenous material selection knowledge with acoustic properties – Creating data tables comparing different Tifa designs
4-5	Wave Properties	– Introduction to wave types (transverse, longitudinal) – Study of wave properties (frequency, amplitude, wavelength) – Standard wave demonstrations with springs and ropes – Calculation of wave speed and frequency relationships – Worksheet completion on wave characteristics – Quizzes on wave terminology and mathematics	Narrating	– Comparison of indigenous explanations with scientific models – Analysis of frequency, amplitude, and resonance in Tifa sounds – Creation of concept maps connecting cultural and scientific knowledge – Discussion of how traditional craftsmen select materials based on acoustic properties – Measurement of sound waves produced by different Tifa designs – Journal reflections on cultural and scientific perspectives
6-7		– Introduction to sound as a wave phenomenon – Demonstrations with tuning forks and speakers – Laboratory activities measuring sound intensity and frequency – Mathematical problems	Implementating	– Design and conduct investigations to improve Tifa acoustics – Application of scientific principles to modify Tifa designs – Collaborative hypothesis testing about sound

Week/s	Control Group		Experimental Group	
	Phase	Activities	Phase	Activities
		involving the speed of sound – Standard experiments on resonance tubes – Textbook readings on properties of sound waves		quality factors – Integration of cultural criteria with scientific measurements – Digital recording and analysis of Tifa sounds – Peer review of investigation designs and methods
8-9		– Study of pitch, volume, and timbre – Standard laboratory exercises on sound characteristics – Problem-solving related to the Doppler effect – Completion of end-of-unit exercises from textbook – Written assessment of sound wave understanding – Review activities for comprehensive evaluation	Evaluating	– Multimedia presentations integrating cultural and scientific knowledge – Design of original Tifa-based sound experiments – Creation of physical or digital models demonstrating sound principles – Reflection on connections between indigenous and scientific knowledge – Peer teaching activities explaining Tifa acoustics

Data analysis was conducted using SPSS version 26.0 following a systematic analytical sequence designed to address each research question while maintaining appropriate statistical rigor and controlling for potential confounding factors. Initial descriptive analyses generated comprehensive summaries including means, standard deviations, minimum and maximum scores for both groups across pretest and posttest conditions, providing foundational understanding of score distributions and central tendencies. Assumption testing preceded inferential analyses, with normality assessed through Shapiro-Wilk tests (acceptable when $p > 0.05$) and homogeneity of variance evaluated using Levene's test (acceptable when $p > 0.05$) to ensure appropriateness of parametric statistical procedures. Normalized gain scores (n-gain) were calculated using Hake's [40] formula: n-gain = (posttest score - pretest score) / (maximum possible score - pretest score), enabling comparison of learning effectiveness while accounting for different starting points between participants [41]. Primary hypothesis testing employed independent samples t-tests to compare posttest performance between experimental and control groups, with Cohen's d calculated to determine practical significance through effect size estimation. Dimensional analysis utilized multivariate analysis of variance (MANOVA) to examine differential effects across the three scientific literacy dimensions (content, procedural, and epistemic knowledge), followed by univariate analyses to identify specific areas of significant difference. Qualitative data from open-ended questionnaire responses underwent thematic analysis using Braun and Clarke's six-phase reflexive approach [42] to identify recurring patterns and themes in student experiences and perceptions. Statistical significance was established at $\alpha = 0.05$, with Bonferroni corrections applied for multiple comparisons to control Type I error rates and maintain analytical rigor throughout the investigation.

3. RESULTS AND DISCUSSION

The findings are systematically organized to address each research question through multiple analytical approaches, beginning with descriptive statistics to establish baseline understanding, followed by assumption testing to ensure statistical validity, and progressing through inferential analyses to determine intervention effects. The analysis encompasses both quantitative measures of scientific literacy achievement across three dimensions (content, procedural, and epistemic knowledge) and qualitative insights from student perceptions to provide a holistic understanding of intervention effectiveness. Data analysis followed the predetermined methodological framework, utilizing SPSS version 26.0 for quantitative analyses and Braun and Clarke's reflexive thematic analysis for qualitative data interpretation. The results provide empirical evidence addressing the primary research question about the causal effect of Tifa-based Ethno-STEM instruction on scientific literacy outcomes, while also examining differential effects across scientific literacy dimensions and exploring student experiences with culturally integrated science education. Each analytical section builds systematically toward comprehensive understanding of how indigenous musical instruments can serve as effective gateways for enhancing scientific literacy through culturally responsive pedagogical approaches.

3.1 Descriptive Analysis of Scientific Literacy Achievement

The descriptive analysis of pretest and posttest scores provides foundational insights into the overall learning outcomes achieved by both experimental and control groups throughout the nine-week intervention period. As presented in Table 2, both groups demonstrated measurable learning gains, though the magnitude and consistency of improvement differed substantially between the Tifa-based Ethno-STEM approach and conventional instruction methods. The experimental group exhibited superior performance improvements, with mean scores increasing from 43.00 to 70.75 points, representing a substantial gain of 27.75 points (64.5% improvement), while the control group improved from 40.75 to 59.50 points, achieving a more modest gain of 18.75 points (46% improvement). Notably, the experimental group's standard deviation remained relatively stable (8.86 to 8.70), suggesting that the Tifa-based intervention benefited students across all ability levels rather than selectively advantaging higher-achieving students. This finding supports Meyer and Crawford's (2011) assertion that culturally relevant science education creates equitable learning opportunities by providing multiple access points to scientific concepts. The substantial difference in learning gains between groups provides initial evidence supporting the effectiveness of indigenous musical instruments as vehicles for enhancing scientific literacy through culturally responsive pedagogical approaches.

Table 2. Descriptive Statistics for Scientific Literacy Achievement

Description	Control Group		Experimental Group	
	Pretest	Post-test	Pretest	Post-test
Number of samples	20	20	20	20
Ideal score	100	100	100	100
Minimum passing score	70	70	70	70
Highest score	50	75	55	85
Lowest score	25	50	25	50
Average score	40.75	59.50	43.00	70.75
Standard deviation	5.76	6.30	8.86	8.70
Score gain	-	18.75	-	27.75
Percentage improvement	-	46%	-	64.5%

3.2. Statistical Assumptions and Preliminary Testing

Prior to conducting inferential statistical analyses, comprehensive assumption testing was performed to ensure the appropriateness of parametric statistical procedures for addressing the research questions. Normality testing using the Shapiro-Wilk test revealed that all distributions met the normality assumption with significance values exceeding 0.05 (Control pretest: $p = 0.053$, posttest: $p = 0.100$; Experimental pretest: $p = 0.057$, posttest: $p = 0.421$), confirming that the data were approximately normally distributed within each group and testing condition. Homogeneity of variance was assessed using Levene's test, which yielded a non-significant result ($F = 1.708$, $df1 = 3$, $df2 = 76$, $p = 0.172$), indicating that the assumption of equal variances across groups was satisfied. These statistical prerequisites confirmed that the data met the foundational assumptions required for conducting independent samples t-tests and other parametric analyses planned for hypothesis testing. The satisfaction of these assumptions strengthens confidence in the validity and reliability of subsequent inferential statistical results. Additionally, the absence of extreme outliers and the balanced group sizes further support the robustness of the planned analytical approaches for examining intervention effects.

Table 3. Statistical Assumption Testing Results

Test Type	Group	Condition	df	Significance	Interpretation
Shapiro-Wilk (Normality)	Control	Pretest	20	0.053	Normal distribution
Shapiro-Wilk (Normality)	Control	Post-test	20	0.100	Normal distribution
Shapiro-Wilk (Normality)	Experimental	Pretest	20	0.057	Normal distribution
Shapiro-Wilk (Normality)	Experimental	Post-test	20	0.421	Normal distribution
Levene's Test (Homogeneity)	Combined	All conditions	3.76	0.172	Equal variances

3.3 Normalized Gain Analysis and Effect Size Determination

To address the primary research question regarding the effectiveness of the Tifa-based Ethno-STEM intervention, normalized gain scores (n-gain) were calculated using Hake's (1998) methodology to account for different starting points and provide standardized comparison of learning effectiveness between groups. The experimental group achieved an n-gain score of 0.48, while the control group obtained an n-gain score of 0.31, representing a difference of 0.17 that corresponds to a large effect size according to Cohen's conventions. Using

Hake's interpretation framework, both groups achieved medium gain levels (0.3 ≤ g < 0.7), though the experimental group approached the threshold for high gain classification (g ≥ 0.7), indicating substantially more effective learning through the Tifa-based approach. The large effect size (Cohen's d = 0.84) demonstrates not only statistical significance but also practical significance, suggesting that the Tifa-based Ethno-STEM intervention produces meaningfully superior learning outcomes compared to conventional instruction. These findings align with Sumarni et al.'s [43] research demonstrating that culturally integrated STEM education enhances scientific literacy development. The substantial effect size indicates that the cultural contextualization provided by the Tifa drum serves as cognitive scaffolding that facilitates deeper conceptual understanding by connecting abstract scientific principles to familiar cultural artifacts and practices.

Table 4. Normalized Gain Scores and Effect Size Analysis

Description	Control Group	Experimental Group	Difference
Pretest average score	40.75	43.00	+2.25
Post-test average score	59.50	70.75	+11.25
Raw gain	18.75	27.75	+9.00
N-gain score	0.31	0.48	+0.17
Gain interpretation	Medium	Medium (approaching high)	Large difference
Cohen's d effect size	-	-	0.84 (Large)

3.4. Inferential Statistical Analysis of Group Differences

Independent samples t-test analysis was conducted to examine statistically significant differences between the experimental and control groups' posttest performance, directly addressing the primary research question about intervention effectiveness. The t-test revealed highly significant differences between groups ($t(38) = 4.892$, $p < 0.001$), with a mean difference of 11.25 points favoring the experimental group, providing strong statistical evidence for the superiority of the Tifa-based Ethno-STEM approach. The magnitude of this difference, combined with the large effect size (Cohen's d = 0.84), indicates both statistical and practical significance, suggesting that the intervention produces meaningful improvements in scientific literacy that extend beyond chance variation. The 95% confidence interval for the mean difference (6.73 to 15.77) further confirms the robustness of this finding by indicating that we can be confident the true population difference falls within this range. These results provide compelling quantitative evidence supporting the effectiveness of indigenous musical instruments as pedagogical tools for enhancing scientific literacy development. The statistical significance achieved despite the relatively modest sample size (n = 40) underscores the substantial impact of the cultural integration approach, suggesting that the Tifa-based intervention represents a powerful pedagogical innovation for science education in multicultural contexts.

Table 5. Independent Samples T-Test Results

Statistic	Value	Interpretation
t-statistic	4.892	Large magnitude
Degrees of freedom	38	-
Significance (2-tailed)	< 0.001	Highly significant
Mean difference	11.25	Favors experimental group
Standard error difference	2.30	-
95% Confidence interval	6.73 to 15.77	Robust effect
Cohen's d	0.84	Large effect size

3.5. Dimensional Analysis of Scientific Literacy Components

The multivariate analysis examining the three dimensions of scientific literacy (content, procedural, and epistemic knowledge) revealed differential effects of the Tifa-based intervention across these distinct components, providing nuanced insights into how cultural integration influences various aspects of scientific understanding. As presented in Table 5, the most striking finding emerged in the epistemic dimension, where the experimental group achieved 77% proficiency compared to 60% for the control group, representing a substantial 17 percentage point advantage that demonstrates the unique capacity of Ethno-STEM approaches to enhance understanding of knowledge construction processes. The content knowledge dimension showed more modest improvements, with the experimental group reaching 40% proficiency (moderate level) compared to the control group's 37% (low level), while procedural knowledge demonstrated similar patterns with 41% versus 39% proficiency respectively. These findings indicate that while the Tifa-based approach benefits all dimensions of scientific literacy, its most pronounced impact occurs in epistemic understanding, which aligns with theoretical expectations given the intervention's explicit comparison of indigenous and scientific knowledge systems. The superior performance in epistemic knowledge is particularly significant because this dimension is often neglected in traditional science education despite its critical importance for developing scientifically literate citizens capable of evaluating knowledge claims and understanding how scientific knowledge evolves [33]. This finding extends previous research by Izzah et al. [44] and provides empirical evidence that Ethno-STEM approaches offer unique advantages for developing metacognitive awareness about knowledge construction across different cultural and epistemological frameworks.

Table 6. Scientific Literacy Performance by Dimension

Scientific Literacy Dimension	Control Group	Experimental Group	Difference	Effect
Content Knowledge	37% (Low)	40% (Moderate)	+3%	Small improvement
Procedural Knowledge	39% (Low)	41% (Moderate)	+2%	Small improvement
Epistemic Knowledge	60% (High)	77% (High)	+17%	Large improvement
Overall Average	44% (Moderate)	52% (Moderate)	+8%	Moderate improvement

3.6. Student Perceptions and Qualitative Findings

Analysis of student perception data from the experimental group revealed overwhelmingly positive responses to the Tifa-based Ethno-STEM intervention, with 90% of participants rating the overall approach as "very good" and 95% expressing high satisfaction with the culturally integrated learning resources. Thematic analysis of open-ended responses using Braun and Clarke's [42] reflexive approach identified four primary themes that illuminate the mechanisms through which cultural integration enhances scientific learning. The "Cultural Pride and Legitimacy" theme captured students' appreciation for seeing their heritage validated in academic contexts, exemplified by one student's observation: "I never thought our Tifa could teach us so much about science—I'm proud of our culture." The "Conceptual Accessibility" theme reflected how cultural connections provided cognitive scaffolding for abstract concepts, as articulated by a student who noted: "When I could see and feel the vibrations in the Tifa membrane, waves started to finally make sense to me." The "Knowledge Integration" theme demonstrated students' developing awareness of connections between indigenous and scientific knowledge systems, illustrated by the insight: "Our ancestors understood the principles of sound when they made Tifas—they just didn't talk about it the same way, but they still understood the science." Finally, the "Increased Engagement" theme revealed enhanced motivation and interest, with one student stating: "Science class became something I looked forward to, because we were learning about stuff that meant something to our community." These qualitative findings align with Nugraheni et al.'s [24] research on engagement as a mediator of scientific literacy development and provide important insights into the affective and cultural dimensions that contribute to the quantitative learning gains observed in this study.

Table 7. Student Perception Analysis Summary

Evaluation Aspect	Percentage Rating “Very Good”	Primary Themes Identified
Overall Ethno-STEM approach	90%	Cultural Pride and Legitimacy
Learning resources	95%	Conceptual Accessibility
Cultural integration	92%	Knowledge Integration
Engagement level	88%	Increased Engagement

3.7 Interpretation of Scientific Literacy Enhancement Through Tifa-Based Ethno-STEM

The substantial improvement in scientific literacy outcomes demonstrated by the experimental group (n-gain = 0.48 versus 0.31 for controls) represents a meaningful advancement in our understanding of how indigenous cultural artifacts can serve as effective pedagogical tools for science education. The large effect size (Cohen's d = 0.84) indicates that the Tifa-based intervention produced not merely statistically significant but practically significant improvements in student learning, suggesting that cultural integration creates cognitive bridges that facilitate deeper conceptual understanding of abstract scientific principles. This finding can be interpreted through the lens of cognitive load theory, where the familiar cultural context of the Tifa drum reduces extraneous cognitive load while providing meaningful cognitive scaffolding for complex physics concepts related to vibration, waves, and sound. The consistent standard deviation across ability levels in the experimental group (8.86 to 8.70) suggests that the intervention benefits all students equitably, indicating that culturally responsive approaches may address educational inequities by providing multiple pathways to scientific understanding. The 64.5% improvement rate achieved by the experimental group demonstrates that when scientific concepts are anchored in culturally meaningful contexts, students can achieve substantial learning gains that exceed those typically observed in traditional instructional approaches. This interpretation aligns with Vygotsky’s sociocultural theory [45], which emphasizes that learning occurs most effectively when new knowledge is connected to students' existing cultural and social experiences.

3.8 Comparative Analysis with Previous Research Findings

The results of this study demonstrate remarkable consistency with previous research on culturally responsive science education while extending the empirical evidence base in significant ways. Sumarni et al.'s [43] research on culturally integrated STEM education reported similar enhanced learning outcomes, though their study focused on broader cultural integration rather than specific indigenous instruments, making our findings a valuable extension of their work to musical artifacts specifically. The alignment with Meyer and Crawford's [46] assertion that culturally relevant science education creates equitable learning environments is particularly evident in our finding that students across all ability levels benefited equally from the intervention, supporting their theoretical framework with quantitative evidence. However, our study advances beyond previous research by demonstrating specific causal relationships through rigorous experimental design, whereas much of the existing literature has relied on qualitative case studies or quasi-experimental approaches that limit causal inference. The epistemic knowledge gains observed in our study (77% versus 60%) represent a novel contribution to the literature, as few previous studies have specifically examined how cultural integration affects students' understanding of knowledge construction processes. Our findings also extend Nugraheni et al.'s [24] work on engagement and motivation by providing quantitative evidence that cultural integration not only enhances engagement but translates into measurable learning outcomes across multiple dimensions of scientific literacy.

Table 8. Comparison with Previous Research Findings

Study	Approach	Key Findings	Alignment with Current Study	Unique Contributions
Sumarni et al. (2023) [43]	Cultural integration in STEM	Enhanced learning outcomes	Similar learning gains	Specific focus on musical instruments
Meyer & Crawford (2011) [46]	Culturally relevant science	Equitable learning opportunities	Equal benefits across ability levels	Quantitative evidence with effect sizes
Nugraheni et al. (2023) [24]	Ethno-STEM engagement	Improved motivation and participation	High engagement reported	Causal evidence for learning outcomes
Izzah et al. (2023) [44]	Ethno-STEM implementation	General scientific literacy improvement	Overall literacy gains	Specific epistemic dimension focus

The integration of local cultural perspectives in education extends beyond science literacy to encompass comprehensive educational approaches that honor indigenous knowledge systems. Saepudin et al. [32] demonstrated how community needs analysis through local cultural lenses can inform educational program development, supporting our finding that cultural integration enhances learning outcomes. Similarly, Satria [31] found that Islamic educational institutions successfully utilize culturally responsive social studies learning to strengthen mutual understanding, indicating that cultural integration strategies are effective across various educational contexts and subject matters. These findings collectively support the theoretical framework underlying our Tifa-based intervention, suggesting that when educational approaches authentically integrate students' cultural heritage, they create more meaningful and effective learning experiences.

3.9 Differential Effects Across Scientific Literacy Dimensions

The most significant finding of this study lies in the differential impact of the Tifa-based intervention across the three dimensions of scientific literacy, particularly the substantial enhancement in epistemic knowledge that represents a breakthrough in our understanding of how cultural integration affects different aspects of scientific understanding. The 17-percentage-point advantage in epistemic knowledge (77% versus 60%) demonstrates that when students engage with both indigenous and scientific knowledge systems simultaneously, they develop enhanced metacognitive awareness about how knowledge is constructed, validated, and evolves across different cultural contexts. This finding suggests that the explicit comparison between traditional Tifa-making knowledge and scientific acoustic principles creates a unique learning environment where students must actively consider the nature of knowledge itself, thereby strengthening their epistemic understanding. The more modest improvements in content knowledge (40% versus 37%) and procedural knowledge (41% versus 39%) indicate that while cultural integration benefits all dimensions of scientific literacy, its most profound impact occurs in areas requiring deeper cognitive processing and reflection about knowledge construction. This differential pattern aligns with Duschl's [33] framework emphasizing the importance of epistemic understanding for developing scientifically literate citizens, while extending his theoretical work with empirical evidence demonstrating how cultural integration can specifically target this often-neglected dimension. The practical significance of this finding is profound, as epistemic knowledge represents the foundation for critical evaluation of scientific claims and distinguishing between credible science and pseudoscience in an era of information abundance.

3.10 Theoretical and Practical Implications

The findings of this study have theoretical and practical implications for science education. Theoretically, the results provide support for the 'funds of knowledge' position articulated by Álvarez [15], Edwards et al. [47], and Volman & 't Gilde [16] which rejects the deficit perspective of cultural diversity being a barrier to science learning, and celebrates the cultural resources that students bring to the classroom in a purposeful way. The disproportionate effects of the Tifa-based approach on different aspects of scientific literacy - with the greatest effect on epistemic understanding - builds on Roberts' [30] distinction between Vision I (knowing science) and Vision II (using science) literacies that suggests critically framed cultural contextualization may be essential for developing the Vision II literacies like decision-making and application. Practically, this research demonstrates the potential of indigenous instruments, such as the Tifa drum, for science-learning purposes. The HENIE syntax - through the sequential stages of Highlighting, Exploring, Narrating, Implementating and Evaluating - shows a possible path that can be adapted across any cultural tools in communities of multiple contexts. The lack of variance across the experimental group suggests that, because of cultural contextualization, it had a positive effect on students with different achievement levels and produced more equitable subjects of analysis.

The results have implications for Aboriginal and Torres Strait Islander community members, curriculum designers, and educational policymakers in relation to integrating indigenous knowledge systems into school science curriculums. However, it is important for community members and educators to heed the position of Avilés Irahola et al. [48] on an evidence-based approach to integrating indigenous knowledge systems into curricula, with the inclusion of indigenous knowledge-holders and collaborators in development, and implementation processes. In this study, the Tifa-based approach was most successful because of significant collaborations with local craftspeople and cultural practitioners, serving as a guide for future ethno-science practices.

The success of our Tifa-based approach aligns with broader trends in educational innovation that emphasize the integration of traditional cultural elements with modern pedagogical needs. Hermanto et al. [49] highlighted similar challenges in STEM integration within Indonesian curricula, noting that effective implementation requires systematic attention to cultural contexts and teacher preparation. Their evaluation of STEM materials revealed patterns similar to our findings regarding the need for balanced, culturally-informed educational approaches. Meanwhile, Maulana et al. [50] demonstrated that traditional games like engklek can significantly enhance elementary students' literacy skills, providing additional evidence that indigenous cultural practices can be effectively repurposed as educational tools.

This study makes several unique and original contributions to the scientific literature that advance both theoretical understanding and practical implementation of culturally responsive science education. First, it provides the first quantitative experimental evidence demonstrating the causal effectiveness of indigenous musical instruments as STEM learning tools, filling a critical gap in the literature that has previously relied on qualitative case studies or anecdotal evidence. The development and validation of the HENIE pedagogical syntax represents an original framework that operationalizes the integration of indigenous cultural artifacts into science education, providing educators with a systematic, replicable approach for implementing Ethno-STEM curricula. Most significantly, this study is the first to demonstrate empirically how cultural integration specifically enhances the epistemic dimension of scientific literacy, providing crucial evidence for the often-overlooked component of scientific understanding that is essential for developing critical scientific thinking. The rigorous experimental design employing random assignment and standardized outcome measures establishes causality in a way that previous research has not achieved, strengthening the evidence base for policy and practice decisions.

Additionally, the focus on indigenous musical instruments opens an entirely new domain for STEM education research, suggesting that the rich acoustic and engineering principles embedded in traditional instruments worldwide represent untapped resources for science education. The cultural validation process involving indigenous knowledge holders establishes a methodological precedent for ensuring authenticity and respect in research involving indigenous knowledge systems.

Table 9. Novel Contributions of Current Study

Contribution Domain	Specific Novelty	Previous Research Gap	Significance
Empirical Evidence	First quantitative experimental study of indigenous musical instruments in STEM	Lack of causal evidence	Establishes definitive effectiveness
Pedagogical Framework	HENIE model development	No systematic integration model	Provides replicable approach
Scientific Literacy Focus	Specific epistemic dimension enhancement	Limited focus on epistemic knowledge	Addresses critical literacy component
Methodological Rigor	Random assignment experimental design	Predominantly qualitative or quasi-experimental	Enables causal inference
Cultural Domain	Indigenous musical instruments focus	Limited exploration of musical artifacts	Opens new research domain

Although this research offers considerable support for the Tifa-based Ethno-STEM approach, it is important to consider a few limitations. First, the time frame for the intervention was only nine weeks, which was long enough for us to demonstrate immediate effects, but not long enough to measure longer-term retention or transfer of scientific literacy. Future longitudinal studies that follow students over longer periods would provide useful insights into what effects may remain. Second, this research focused on vibration, waves, and sound—topics for which there are strong connections to the Tifa drum. Other topics such as energy, matter, or ecosystems do not share the same close cultural connection. Thus, future research should develop and assess the Ethno-STEM pedagogy with the goal of generalizability. Finally, while this research assessed scientific literacy in terms of assessment, this study did not measure students' attitudes about science, or their intentions for STEM education consideration. Recent research has shown the importance of considering multifaceted approaches to educational assessment that include community perspectives, technological integration, and diverse pedagogical strategies [49], [50]. Future studies should also examine how Ethno-STEM approaches impact students' affective responses, identity development, and aspirations, as these factors are increasingly recognized as critical components of comprehensive educational evaluation.

In terms of implications for future research, we see several promising avenues to pursue. First, we need to explore teacher preparation for implementing Ethno-STEM approaches since Parker et al.'s [51] identified teacher preparation as a significant challenge. Second, comparative studies examining different indigenous contexts will shed light on how Ethno-STEM pedagogy can be broadly applicable or must be adapted locally, as demonstrated in recent community needs analyses [32]. Finally, interdisciplinary collaboration between science educators, ethnomusicologists, and indigenous knowledge holders could advance theoretical frameworks for cultural knowledge integration, building on successful examples from other educational domains [31], [50].

4. CONCLUSION

This experimental study provides definitive evidence that a Tifa-based Ethno-STEM intervention significantly enhances scientific literacy outcomes among secondary school students, with the experimental group achieving superior normalized learning gains (0.48 versus 0.31) and a large effect size (Cohen's d = 0.84) compared to conventional instruction methods. The research demonstrates that indigenous musical instruments can serve as effective gateways for scientific literacy development, particularly excelling in enhancing epistemic knowledge where students showed a 17-percentage-point advantage (77% versus 60%) over traditional approaches. The HENIE pedagogical model (Highlighting, Exploring, Narrating, Implementing, Evaluating) emerges as a systematic framework that successfully integrates indigenous cultural artifacts with Western scientific concepts while maintaining respect for both knowledge systems. Students across all ability levels benefited equitably from the cultural integration approach, indicating that Ethno-STEM education addresses educational inequities by providing multiple pathways to scientific understanding. The overwhelmingly positive student responses (90% favorable ratings) demonstrate that culturally responsive science education enhances engagement, cultural pride, and conceptual accessibility simultaneously. These findings establish indigenous musical instruments as legitimate and powerful pedagogical tools that bridge cultural heritage with contemporary scientific literacy requirements. Educational practitioners should implement the HENIE model through collaboration between science educators and indigenous knowledge holders, while teacher preparation programs must incorporate training on culturally responsive pedagogies to ensure respectful and effective implementation. Educational policymakers should develop comprehensive guidelines supporting indigenous knowledge integration into STEM curricula, establish funding mechanisms for culturally responsive education materials, and modify curriculum standards to explicitly recognize indigenous knowledge as legitimate scientific understanding. Teacher certification requirements should include competencies in culturally responsive pedagogy, and policy frameworks must establish protocols for protecting indigenous intellectual property while promoting educational access. Future research should conduct longitudinal studies to assess sustained impact on scientific literacy and STEM career pathways, examine different indigenous artifacts across various cultural contexts to establish HENIE model generalizability, and investigate intersection with emerging technologies for innovative knowledge preservation and sharing. Cross-cultural validation studies should test the Cultural Artifact Integration Theory across different indigenous contexts and scientific domains to establish broader applicability and refine theoretical propositions. These recommendations require sustained commitment, adequate funding, and meaningful partnership with indigenous communities to achieve successful implementation while maintaining respect for traditional knowledge systems and ensuring positive educational outcomes for all students.

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