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Research Article

Modeling the impact of interactive ethno-STEM learning materials on students' 21st-century skills: A structural equation modeling approach

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In the evolving educational landscape, the integration of culturally responsive STEM education is critical for developing 21st-century competencies. This study modeled the impact of interactive ethno-STEM learning materials infused with ethno-scientific and local cultural contexts, on students' critical thinking, creativity, collaboration, and communication skills. A cross-sectional design involving 385 senior high school students in West Sumatra was analyzed using Structural Equation Modeling. Results show that exposure to ethno-STEM learning materials significantly enhanced perceived usefulness, cultural relevance, and learning engagement, with strong model fit indices. Lerning engagement was the strongest predictor of skill development, while cultural relevance particularly supported creativity. The indirect effects on 21st-century skills were substantial, demonstrating that student perceptions serve as key mediating pathways. These findings highlight the role of culturally embedded, interactive learning in driving 21st-century skill acquisition and provide a validated predictive framework to strengthen culturally responsive STEM instruction in diverse educational settings.

Keywords: 21st-century skills; Cultural relevance; Ethno-STEM; Learning engagement; Structural equation modeling

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1. Introduction

The rapid evolution of science and technology in the 21st century has transformed expectations in education, particularly in cultivating students' cognitive, interpersonal, and intrapersonal competencies (Cahapay, 2023; Ezmeci, 2023; Wang et al., 2018). Among these the 4C—critical thinking, creativity, communication, and collaboration—are widely recognized as essential for students' academic success and active participation in society (Chalkiadaki, 2018; Supena et al., 2021). As a response, modern educational reforms emphasize interdisciplinary, technology-supported, and contextually grounded learning environments, particularly within science education (Baran et al., 2021; Liesa-Orús et al., 2020).

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To meet these demands, STEM-integrated instructional models have been widely implemented to support experiential, project-based, and problem-centered learning (Stohlmann, 2019; Yusuf et al., 2018). However, a key critique of many STEM initiatives is their lack of cultural contextualization, which may reduce relevance and engagement for students who struggle to connect scientific concepts to their lived experiences (Zakiyah & Sudarmin, 2022). In response, ethno-STEM, which integrates local cultural knowledge (ethnoscience) into STEM learning, has emerged as a culturally responsive approach that promotes meaningful and relevant learning experiences (Sari et al., 2023; Sumarni & Kadarwati, 2020).

In the context of physics education, often perceived as abstract and disconnected from daily life, ethno-STEM learning materials provide opportunities for students to explore scientific ideas through familiar cultural practices, enhancing inquiry, collaboration, and innovation (Ardianti & Raida, 2022; N et al., 2023). Although previous studies have reported improved scientific literacy and engagement through such materials (N et al., 2025; Asrizal et al., 2025), they rarely explain how these outcomes occur, particularly in terms of the psychological mechanisms underlying 21st-century skill development.

Recent research emphasizes the need to investigate the interrelationships among learning perceptions and higher-order skills using robust analytical approaches such as Structural Equation Modeling [SEM] (Ciarli et al., 2021; Fatmawati et al., 2019). Grounded in Self- Determination Theory [SDT], which posits autonomy, relatedness, and competence as drivers of motivation, culturally meaningful learning experiences are expected to enhance engagement and subsequently promote the acquisition of advanced competencies (Ryan & Deci, 2020). From a constructivist perspective, learning becomes effective when students integrate new ideas with prior cultural and experiential knowledge, positioning Ethno- STEM as a theoretically and pedagogically significant model.

Accordingly, this study models the influence ethno-STEM learning materials on students' 21st-century skills using SEM. It will investigate the direct and indirect effects of key latent constructs, such as perceived usefulness, cultural relevance, and learning engagement, on the development of critical thinking, creativity, communication, and collaboration. By doing so, the study contributes novel insights to the theory of culturally responsive STEM education and offers practical implications for curriculum designers and policymakers seeking to implement transformative instructional practices in science classrooms.

Based on this background, the research aims to address the following questions:

RQ 1) How do interactive ethno-STEM learning materials influence students' perceived engagement, cultural relevance, and usefulness in the context of physics learning?

RQ 2) To what extent do these perceptions affect the development of students' 21st-century skills (critical thinking, creativity, collaboration, and communication)?

RQ 3) What are the structural relationships among engagement, perceived usefulness, cultural relevance, and the acquisition of 21st-century skills as revealed through SEM?

This study isexpected to fill a crucial theoretical gap by proposing and validating a comprehensive model grounded in both cultural pedagogical theory and STEM education. It advances prior literature by moving beyond effectiveness testing and toward predictive modeling of learning outcomes. A methodological leap aligned with the standards of high-impact, Q1-level educational research.

2. Literature Review

2.1. Ethno-STEM Learning Materials in Physics Education

The integration of STEM with ethnoscience, referred to as ethno-STEM, has emerged as a culturally responsive approach to enhance the contextual relevance of science learning. By situating abstract scientific concepts within students' cultural and local knowledge systems, ethno-STEM encourages meaningful learning and strengthens engagement (Sumarni & Kadarwati, 2020; Zakiyah & Sudarmin, 2022). These materials connect traditional cultural practice science principles, promoting inquiry and deeper conceptual understanding in physics contexts (Ardianti & Raida, 2022; Sari et al., 2023). Evidence suggests that interactive materials, including digitally mediated resources, enhance autonomy and participation, thereby supporting creativity and problem-solving skills (Abadi et al., 2017; Mertasari & Candiasa, 2022). However, prior research has focused primarily on evaluating learning outcomes rather than explaining the underlying psychological mechanisms that shape skill development. To address this limitation, it is essential to examine how students' perceptions such as perceived usefulness, cultural relevance, and engagement mediate the influence of ethno-STEM materials on learning outcomes.

2.2. Perceived Usefulness, Cultural Relevance, and Learning Engagement

Perceived usefulness plays a central role in determining whether students adopt and meaningfully engage with learning resources (Liesa-Orús et al., 2020). When students perceive learning materials as useful for achieving academic goals, they are more likely to engage cognitively and behaviorally (Yusuf et al., 2018). Cultural relevance similarly strengthens learning by connecting instructional content with students' identities, values, and lived experiences, which enhances motivation and sustained engagement (Sari et al., 2023; Zakiyah & Sudarmin, 2022). Within this context, ethno-STEM materials are well positioned to foster these positive perceptions by embedding culturally meaningful contexts into scientific learning. This relationship between culturally responsive instructional practices and student engagement has also been highlighted in pedagogical research, emphasizing that alignment between learning content and students' cultural backgrounds promotes meaningful participation across diverse classroom contexts (Anyichie et al., 2023). From the perspective of Self-Determination Theory [SDT], learning engagement increases when instructional environments satisfy students' needs for autonomy, relatedness, and competence (Ryan & Deci, 2020). Culturally contextualized and interactive learning experiences are therefore expected to enhance engagement, positioning it as a theoretically grounded mediator linking instructional design to learning outcomes. Consequently, examining perceived usefulness, cultural relevance, and engagement is essential for understanding how learning experiences contribute to the development of higher-order competencies.

2.3. 21st-Century Skills and Their Development

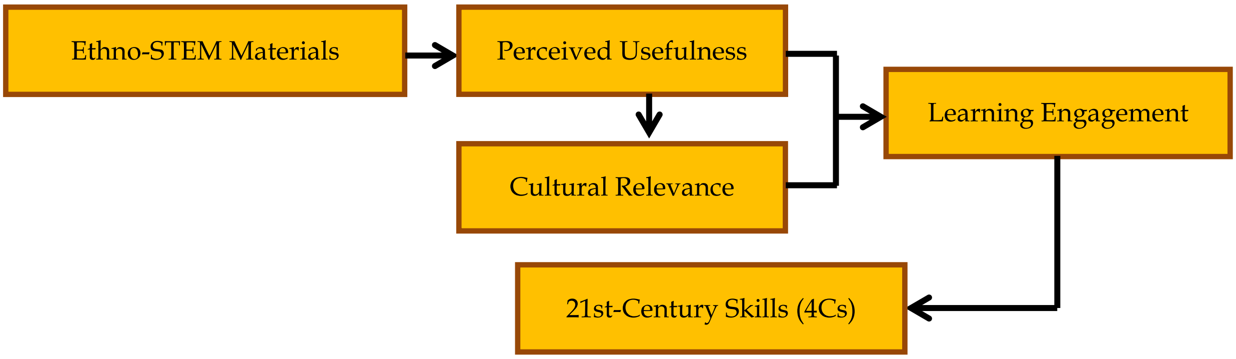
The framework of 21st-century skills, particularly the 4Cs critical thinking, creativity, collaboration, and communication, has become a global educational benchmark (Baran et al., 2021; Supena et al., 2021). These competencies are not only necessary for academic success but also for innovation and workforce readiness in the digital age (Ciarli et al., 2021; Wang et al., 2018;). Prior empirical studies have demonstrated that STEM education can improve these skills, particularly when implemented through inquiry-based, project-based, or technology-enhanced learning environments (Alpindo et al., 2022; Triana et al., 2020). However, the specific role of ethno-STEM materials, particularly their perceived usefulness, cultural fit, and capacity to engage learners in promoting these skills, remains underexplored in current literature. Moreover, most studies assessing 21st-century skills have relied on pre-post experimental designs rather than structural models that explain causal or mediating relationships among learning variables (Asrizal et al., 2025; Novitra et al., 2021). Thus, a predictive model using SEM can offer deeper insight into how and why ethno-STEM learning materials foster the 4Cs.

2.4. Research Gap and Theoretical Contribution

Although interest in culturally grounded STEM pedagogy continues to grow, no study has comprehensively modeled the mechanisms through which ethno-STEM instruction influences 21st-century skills. In particular, the mediating roles of perceived usefulness, cultural relevance, and learning engagement remain underexplored in physics education contexts. The present study extends existing conceptual and empirical models by developing and validating a predictive Structural Equation Model that explains the pathways linking ethno-STEM materials to students' 21st-century competencies. By integrating insights from culturally responsive pedagogy and Self-

Determination Theory, this study offers a theoretically grounded explanation of how engagement functions as a key mediator. Accordingly, the conceptual framework presented in Figure 1 summarizes the proposed relationships among the study variables.

Figure 1
Proposed conceptual framework



3. Methods

3.1. Research Design

This study employed a cross-sectional quantitative research design utilizing SEM to examine the relationships between interactive ethno-STEM learning materials and students' 21st-century skills development. The design enabled the analysis of complex causal pathways among multiple latent constructs and was aligned with contemporary methodological priorities in educational research, which emphasize predictive modeling rather than simple effectiveness testing (Hair et al., 2019; Kline, 2016). A non-experimental correlational framework was adopted because it is appropriate for investigating structural relationships among perceived usefulness, cultural relevance, learning engagement, and 21st-century skills without manipulation of independent variables (Field, 2018). This approach corresponds with established educational psychology research practices that emphasize naturally occurring relationships (Creswell & Creswell, 2018; Tabachnick, & Fidell, 2019).

3.2. Research Setting and Context

The study was conducted in public senior high schools in West Sumatra, Indonesia, where interactive Ethno-STEM learning materials had been implemented for physics instruction for at least one semester. Schools were selected based on active application of ethno-STEM approaches, availability of interactive learning resources, and institutional willingness to participate. The context was particularly relevant due to ongoing integration of Minangkabau cultural elements into physics instruction (N et al., 2023), providing a suitable environment for analyzing culturally responsive STEM learning.

3.3. Participants

Participants were selected using purposive sampling to ensure that all respondents had direct experience with interactive ethno-STEM learning materials in physics education (Creswell & Creswell, 2018; Patton, 2015). The sample included 385 Grade 11 science-track students, exceeding the minimum sample size recommended for SEM, which ranges from 10–15 participants per parameter (Kline, 2016), and meeting guidelines for large-scale structural models (Hair et al., 2019). Demographic characteristics are presented in Table 1.

Table 1
Demographic Characteristics of Study Participants (N = 385)

Categories	*Frequency*	*Percentage*
Gender		
Male	178	46.2%
Female	207	53.8%
Age		
16 years	142	36.9%
17 years	201	52.2%
18 years	42	10.9%
School Type		
Urban	231	60.0%
Rural	154	40.0%
Previous Physics Grade		
A (90-100)	89	23.1%
B (80-89)	178	46.2%
C (70-79)	118	30.7%
Ethnicity		
Minangkabau	298	77.4%
Javanese	45	11.7%
Batak	28	7.3%
Others	14	3.6%
Duration of Ethno-STEM Exposure		
1 semester	156	40.5%
2 semesters	138	35.8%
3+ semesters	91	23.6%

3.4. Instrumentation

A comprehensive survey consisting of validated scales was used to measure the constructs included in the proposed structural model. All questionnaire items utilized a 5-point Likert response format ranging from 1 (strongly disagree) to 5 (strongly agree), allowing respondents to express varying degrees of agreement and ensuring sensitivity in capturing attitudinal and behavioral differences. To ensure linguistic accuracy and cultural appropriateness, all instruments were translated into Bahasa Indonesia using a translation and back-translation procedure, following the guidelines established by Brislin (1970). Expert reviews were conducted to confirm content clarity, equivalency, and contextual suitability prior to full-scale administration.

3.4.1. Ethno-STEM materials exposure scale

Exposure to interactive ethno-STEM materials was measured using a 12-item researcher-developed scale created to capture students' level of interaction with culturally integrated physics learning materials. The scale quantified the frequency of material usage (e.g., number of class sessions per week), duration of exposure (number of semesters), and types of learning interactions experienced by students, including digital simulations, hands-on activities, and project-based tasks that integrated local cultural elements. Item development was guided by established frameworks for evaluating instructional materials and was subjected to validation through expert review and pilot testing to ensure clarity and structural validity (DeVellis, 2017). The resulting instrument provided a comprehensive measure of students' engagement with ethno-STEM implementations within the learning environment.

3.4.2. Perceived Usefulness Scale

Perceived usefulness was assessed using an adapted 8-item scale derived from the Technology Acceptance Model (Davis, 1989). The scale measured students' beliefs regarding the extent to which interactive ethno-STEM materials enhanced their learning effectiveness, understanding of physics concepts, and overall academic performance. Items were recontextualized for educational settings to align with classroom-based technology usage requirements while maintaining conceptual integrity. Respondents indicated their level of agreement with statements addressing the benefits and practical value of the learning resources provided.

3.4.3. Cultural Relevance Scale

Cultural relevance was measured using a 10-item scale adapted from the framework developed by Gay (2018). This instrument assessed students' perceptions of the degree to which the learning materials reflected their cultural identity, local knowledge traditions, and everyday experiences. The scale emphasized the importance of instructional alignment with cultural context as a means of strengthening meaningful learning. Items captured students' recognition of cultural representation within physics learning activities, ensuring theoretical grounding in culturally responsive pedagogy.

3.4.4. Learning Engagement Scale

Learning engagement was evaluated using the 18-item Student Engagement Scale developed by Fredricks et al. (2016), which measured behavioral, emotional, and cognitive aspects of student participation in learning activities. The instrument captured students' active involvement in classroom practices, emotional responses to instructional experiences, and depth of cognitive processing during the learning process. Each dimension was represented by six items, providing a balanced assessment of engagement across multiple components. The scale has been widely recognized for its strong psychometric properties in diverse educational contexts.

3.4.5. 21st-Century Skills Assessment

Assessment of 21st-century skills utilized an adapted version of the Partnership for 21st Century Learning [P21] (2019) framework consisting of 32 items. The instrument measured four core skill domains critical thinking, creativity, collaboration, and communication through scenario-based items situated within physics learning contexts, ensuring authenticity and practical relevance. Each set of items was designed to reflect real-world problem-solving requirements, group work dynamics, and communication competencies necessary for modern scientific literacy. This approach provided an ecologically valid evaluation of students' skill development.

3.4.6. Reliability Summary

To ensure consistency and accuracy of measurement across all instruments, internal reliability analyses were conducted, and results demonstrated strong internal consistency for each scale. Table 2 presents a summary of Cronbach's alpha values based on previously established psychometric evidence, all of which exceeded accepted reliability thresholds. Consolidating these values in a single table facilitates clarity and transparent reporting of measurement quality. The strong reliability coefficients indicate that the instruments used were appropriate for SEM-based inferential analysis.

Table 2
Reliability summary of study instruments

Construct	*Items*	*Cronbach's α*
Ethno-STEM Exposure	12	.91
Perceived Usefulness	8	.88
Cultural Relevance	10	.93
Learning Engagement	18	.92
21st-Century Skills	32	.95

3.5. Research Hypotheses

Based on the proposed conceptual framework, the following hypotheses were formulated and tested in this study.

H1: Exposure to interactive ethno-STEM materials positively influences perceived usefulness.

H2: Exposure to interactive ethno-STEM materials positively influences cultural relevance.

H3: Perceived usefulness, cultural relevance, and learning engagement significantly predict 21st-century skills.

H4: Learning engagement mediates the relationship between exposure and 21st-century skills.

H5: Indirect effects through mediating variables are stronger than direct effects.

3.6. Data Collection Procedures

Data collection occurred over six weeks during the second semester of the 2023–2024 academic year. Ethical approval was obtained prior to data collection, and informed consent procedures followed recommended research ethics standards, including parental consent for minors (American Educational Research Association, 2011). Surveys were administered during scheduled class periods under standardized supervision to ensure consistency and data integrity. Anonymity and voluntary participation were emphasized. To address potential common method bias, procedural remedies were implemented (such as anonymous responses and randomized item presentation), and statistical verification was conducted using Harman's single-factor test, which showed that the first factor accounted for 27.5% of variance, below the 50% threshold, indicating minimal common method bias.

3.7. Data Analysis Strategy

The following SEM procedures were conducted to test hypotheses H1–H5, including direct effects of ethno-STEM exposure on mediators and indirect effects on 21st-century skills. Data analysis proceeded through several sequential phases, comprising descriptive statistics, reliability testing, CFA, and SEM. Preliminary screening included examination of missing values, identification of multivariate outliers using Mahalanobis distance, and assessment of normality based on skewness and kurtosis values. Missing data were addressed using full information maximum likelihood [FIML] estimation under the missing at random assumption (Little & Rubin, 2020), and Harman's single-factor test was performed to reduce potential common method bias.

Measurement model evaluation was conducted through CFA using Mplus version 8.8, assessing model fit using χ^2, CFI, TLI, RMSEA, and SRMR following Hu and Bentler's (1999) recommended cutoffs (CFI/TLI ≥ .95, RMSEA ≤ .06, SRMR ≤ .08). Reliability was examined using Cronbach's alpha and composite reliability (≥ .70 acceptable), convergent validity through factor loadings (≥ .50) and AVE (≥ .50), and discriminant validity through Fornell–Larcker and HTMT criteria (Hair et al., 2019).

Structural model testing was conducted using SEM with maximum likelihood estimation and robust standard errors to address potential non-normality. The model tested direct effects from perceived usefulness, cultural relevance, and learning engagement to the four 21st-century skills dimensions, as well as indirect effects to evaluate mediation pathways. Mediation testing utilized bootstrapping with 5,000 resamples and bias-corrected confidence intervals. Competing models were compared using AIC, BIC, and χ^2-difference tests to identify the most parsimonious model. Hypotheses were tested at α = .05.

4. Results

4.1. Preliminary Data Analysis and Model Assessment

Before addressing the research questions, comprehensive preliminary analyses were conducted to ensure data quality and model appropriateness. The final dataset included 385 complete responses with minimal missing data (< 2% across all variables). Multivariate normality was assessed through examination of skewness and kurtosis values, which ranged from −1.42 to 1.38, indicating an acceptable range for SEM analysis (Kline, 2016). Mahalanobis distance calculations identified seven multivariate outliers, which were retained following confirmation that they reflected legitimate response patterns rather than data entry errors.

The measurement model demonstrated excellent overall fit (χ^2 = 892.45, df = 487, CFI = .952, TLI = .947, RMSEA = .047, SRMR = .058). All factor loadings exceeded .60, with the majority surpassing .75, indicating strong convergent validity. Composite reliability values ranged from .84 to .93 and AVE values ranged from .52 to .68, supporting reliability and validity assumptions. Discriminant validity was established through the Fornell–Larcker criterion and HTMT ratios below .85. Before interpreting subsequent findings, Table 3 presents descriptive statistics, reliability coefficients, and intercorrelations among study variables to provide an overview of general trend patterns and construct associations.

Table 3
Descriptive Statistics, Reliability Coefficients, and Intercorrelations among Study Variables

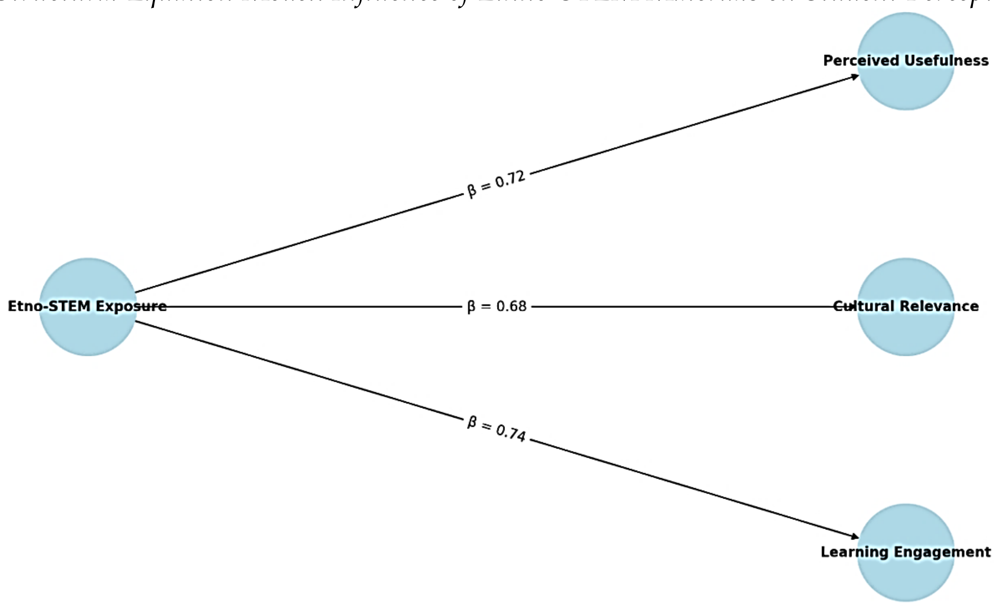
Construct	*Mean*	*SD*	*α*	*CR*	*AVE*	*1*	*2*	*3*	*4*	*5*	*6*	*7*
1. Ethno-STEM Exposure	4.12	0.68	.87	.88	.55	–						
2. Perceived Usefulness	4.23	0.62	.91	.92	.61	.72	–					
3. Cultural Relevance	4.08	0.71	.89	.90	.58	.68	.71	–				
4. Learning Engagement	4.18	0.65	.93	.94	.68	.74	.78	.69	–			
5. Critical Thinking	3.89	0.73	.88	.89	.56	.59	.65	.58	.71	–		
6. Creativity	3.76	0.79	.86	.87	.52	.54	.61	.63	.68	.73	–	
7. Collaboration	4.02	0.72	.90	.91	.62	.61	.66	.64	.72	.68	.71	–
8. Communication	3.94	0.76	.84	.85	.53	.57	.62	.59	.69	.70	.68	.74

Note. N = 385. *α* = Cronbach's alpha; CR = Composite Reliability; AVE = Average Variance Extracted; *p* < .01.

4.2. Research Question 1: Influence of Interactive Ethno-STEM Materials on Student Perceptions

Table 4 summarizes the direct effects of ethno-STEM exposure on students' perceived usefulness, cultural relevance, and learning engagement. These results highlight the relative magnitude and statistical strength of each pathway. The first research question examined how interactive ethno-STEM learning materials influence students' perceived engagement, cultural relevance, and usefulness in physics learning contexts. Path analysis within the structural equation model revealed significant positive relationships between exposure to interactive ethno-STEM materials and all three mediating constructs.

Figure 2
Structural Equation Model: Influence of Ethno-STEM Materials on Student Perceptions



As summarized in Figure 2, ethno-STEM exposure demonstrated a strong positive relationship with perceived usefulness (β = .72, p < .001, 95% CI [.66, .78]), explaining 52% of the variance in the perception of usefulness (R^2 = .52). The standardized coefficient for cultural relevance indicated a strong effect (β = .68, *p* < .001, R^2 = .46), suggesting meaningful improvement in relevance perceptions. The strongest predictive relationship emerged for learning engagement, with a very strong effect (β = .74, *p* < .001, R^2 = .55), demonstrating substantial enhancement of student involvement and motivation.

Similarly, the relationship between ethno-STEM exposure and cultural relevance yielded a standardized coefficient of .68 (*p* < .001, 95% CI [.61, .75]), with an R^2 of .46 (see Table 4). This substantial effect size demonstrates that interactive ethno-STEM materials successfully connected physics concepts with students' cultural backgrounds and lived experiences. The strength of this relationship is particularly noteworthy given the diverse ethnic composition of the sample, suggesting that the materials effectively resonated across different cultural groups within the study population.

Table 4

Direct Effects of Interactive Ethno-STEM Materials on Student Perceptions

Path	*β*	*SE*	*z*	*p*	*95% CI*	*R^2*
Ethno-STEM → Perceived Usefulness	.72	.031	23.23	<.001	[.66, .78]	.52
Ethno-STEM → Cultural Relevance	.68	.035	19.43	<.001	[.61, .75]	.46
Ethno-STEM → Learning Engagement	.74	.028	26.43	<.001	[.68, .80]	.55

The strongest relationship emerged between ethno-STEM exposure and learning engagement, with a standardized coefficient of .74 (*p* < .001, 95% CI [.68, .80]) and an R^2 of .55. This finding indicates that interactive ethno-STEM materials were particularly effective in promoting active participation, emotional investment, and cognitive processing among students. The magnitude of this effect suggests that the combination of interactive features and cultural contextualization creates a synergistic impact on student engagement that exceeds what might be achieved through either element alone.

4.3. Research Question 2: Impact of Student Perceptions on 21st-Century Skills Development

The second research question investigated the extent to which student perceptions of usefulness, cultural relevance, and engagement affect the development of 21st-century skills. The structural equation model revealed differential patterns of influence across the four skill domains, with learning engagement consistently emerging as the strongest predictor of skill development. Table 5 presents the direct effects and total explained variance for each skill domain.

Table 5

Direct Effects of Student Perceptions on 21st-Century Skills

Outcome Variable	*Perceived Usefulness*	*Cultural Relevance*	*Learning Engagement*	*Total R^2*
	β (SE)	β (SE)	β (SE)	
Critical Thinking	.18 (.042)	.12 (.038)	.51 (.035)	.58
Creativity	.22 (.045)	.28 (.041)	.38 (.039)	.61
Collaboration	.16 (.043)	.19 (.040)	.48 (.037)	.59
Communication	.21 (.044)	.15 (.041)	.45 (.038)	.56

Note. Standardized coefficients reported. *p* < .05, *p* < .01, *p* < .001.

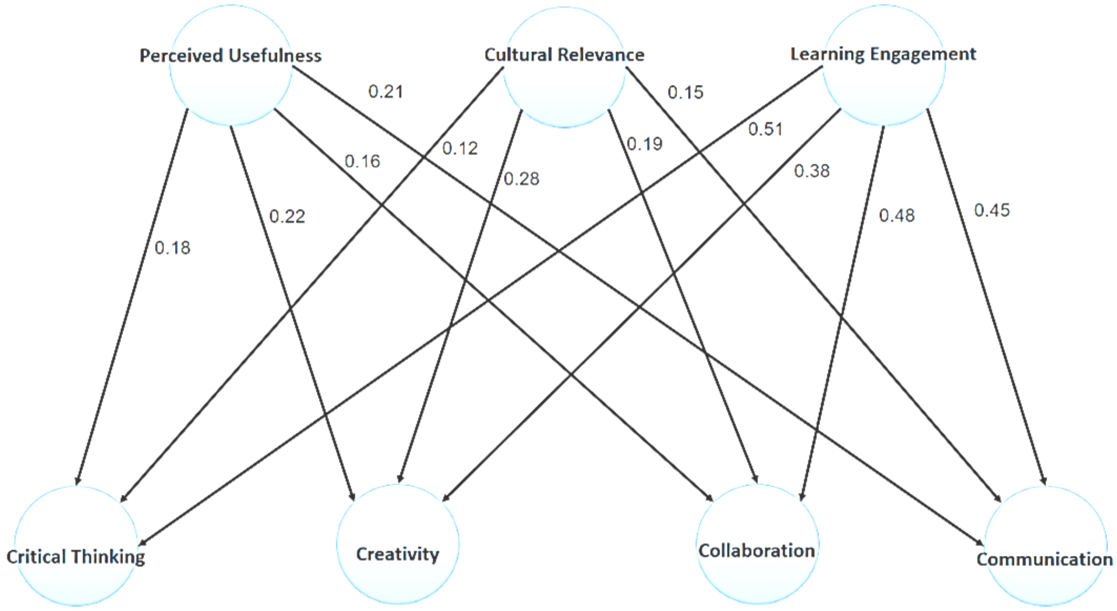
For critical thinking skills, learning engagement demonstrated the strongest predictive relationship (β = .51, *p* < .001), followed by perceived usefulness (β = .18, *p* < .05) and cultural relevance (β = .12, *p* < .05). The combined model explained 58% of the variance in critical thinking skills, indicating substantial predictive power. The dominance of learning engagement in predicting critical thinking aligns with theoretical expectations, as engaged students are more likely to invest cognitive resources in analyzing information, evaluating evidence, and constructing logical arguments, core components of critical thinking.

Creativity showed a more balanced pattern of prediction, with cultural relevance emerging as a particularly strong predictor (β = .28, p < .001), alongside learning engagement (β = .38, p < .001) and perceived usefulness (β = .22, p < .01). The model explained 61% of the variance in creativity, representing the highest explained variance among the four skills. The prominent role of cultural relevance in predicting creativity is theoretically significant, as it suggests that connecting learning content to students' cultural backgrounds provides cognitive flexibility and alternative perspectives that foster creative thinking processes.

Collaboration skills were most strongly predicted by learning engagement (β = .48, p < .001), followed by cultural relevance (β = .19, p < .01) and perceived usefulness (β = .16, p < .05). The model accounted for 59% of the variance in collaboration skills. The strong relationship between engagement and collaboration reflects the interactive nature of engaged learning, where students are more likely to participate actively in group discussions, share ideas effectively, and contribute meaningfully to collective problem-solving efforts.

Communication skills demonstrated similar patterns, with learning engagement as the primary predictor (β = .45, p < .001), followed by perceived usefulness (β = .21, p < .01) and cultural relevance (β = .15, p < .05). The model explained 56% of the variance in communication skills. The strength of the engagement-communication relationship suggests that students who are emotionally and cognitively invested in their learning are more motivated to express their ideas clearly and engage in meaningful dialogue with peers and instructors. Figure 3 illustrates the structural equation model depicting the relationships between student perceptions and the four domains of 21st-century skills.

Figure 3
Structural Equation Model: Impact of Student Perceptions on 21st-Century Skills

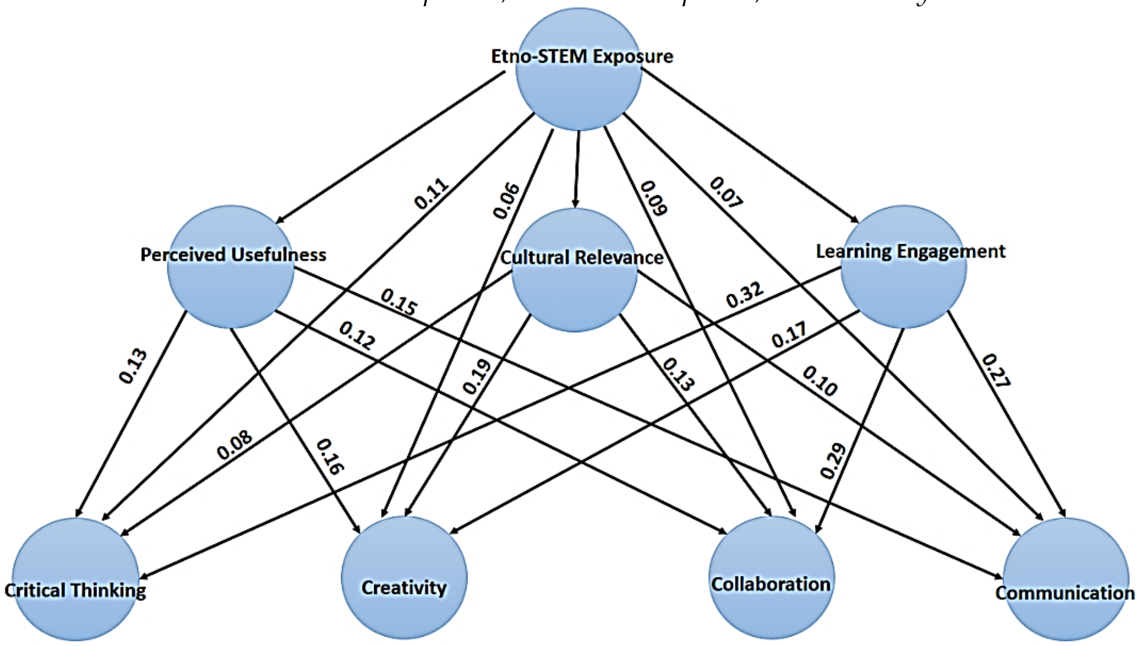


The differential patterns of prediction across skills reveal important insights about the mechanisms through which student perceptions influence skill development. Learning engagement consistently emerged as the strongest predictor across all four skills, reflecting its fundamental role as a catalyst for deep learning processes. When students are behaviorally, emotionally, and cognitively engaged, they are more likely to practice and develop higher-order thinking skills through active participation in learning activities.

4.4. Research Question 3: Structural Relationships and Mediation Effects

The third research question examined the structural relationships among engagement, perceived usefulness, cultural relevance, and 21st-century skills acquisition through comprehensive mediation analysis. The full structural model demonstrated excellent fit (χ^2 = 1,247.33, df = 712, p < .001; CFI = .949, TLI = .945, RMSEA = .044 [90% CI: .040, .048], SRMR = .062), supporting the proposed theoretical framework. Figure 4 presents the full mediation model illustrating the structural relationships between ethno-STEM exposure, student perceptions, and 21st-century skills.

Figure 4
Mediation Model: Ethno-STEM Exposure, Student Perceptions, 21st-Century Skills



Bootstrap analysis with 5,000 resamples revealed significant indirect effects from ethno-STEM exposure to all four 21st-century skills through the three mediating constructs. The total indirect effects were substantial, ranging from .52 to .58 across the four skills, indicating that the majority of the relationship between ethno-STEM materials and skill development operates through student perceptions rather than direct mechanisms. Table 6 reports the decomposition of total, direct, and indirect effects for each 21st-century skill domain based on the bootstrap mediation analysis.

Bootstrap 95% confidence intervals based on 5,000 resamples.The mediation analysis revealed that learning engagement served as the primary mediating pathway for critical thinking, collaboration, and communication skills, with specific indirect effects ranging from .27 to .32. This finding underscores the central role of student engagement as a mechanism through which interactive ethno-STEM materials influence skill development. When students are actively engaged in learning activities, they are more likely to practice analytical reasoning, participate in collaborative discussions, and communicate their ideas effectively.

For creativity skills, the mediation pattern was more distributed across all three mediators, with cultural relevance showing the strongest specific indirect effect (.19), followed by perceived usefulness (.16) and learning engagement (.17). This balanced mediation pattern suggests that creativity development benefits from multiple psychological mechanisms operating simultaneously. Cultural relevance provides diverse perspectives and alternative thinking strategies, perceived usefulness motivates sustained effort in creative tasks, and engagement facilitates the active exploration necessary for creative insight.

Table 6

Decomposition of Effects: Total, Direct, and Indirect Effects

Skill Domain	*Total Effect*	*Direct Effect*	*Total Indirect Effect*	*Specific Indirect Effects*		
	β (95% CI)	β (95% CI)	β (95% CI)	Via PU	Via CR	Via LE
Critical Thinking	.64 [.58, .70]	.11 [.04, .18]	.53 [.46, .60]	.13 [.09, .17]	.08 [.05, .12]	.32 [.26, .38]
Creativity	.58 [.52, .64]	.06 [−.01, .13]	.52 [.45, .59]	.16 [.11, .21]	.19 [.14, .24]	.17 [.12, .22]
Collaboration	.63 [.57, .69]	.09 [.02, .16]	.54 [.47, .61]	.12 [.08, .16]	.13 [.09, .17]	.29 [.24, .34]
Communication	.59 [.53, .65]	.07 [.00, .14]	.52 [.45, .59]	.15 [.11, .19]	.10 [.06, .14]	.27 [.22, .32]

Note. PU = Perceived Usefulness; CR = Cultural Relevance; LE = Learning Engagement.

The direct effects from ethno-STEM exposure to 21st-century skills were relatively small and marginally significant, ranging from .06 to .11. This pattern indicates that interactive ethno-STEM materials primarily influence skill development through their impact on student perceptions and subsequent psychological processes rather than through direct instructional mechanisms. The dominance of indirect effects supports theoretical models that emphasize the importance of student psychological responses to instructional innovations.

Collectively, these results provide strong empirical support for the proposed mediation framework, demonstrating that ethno-STEM interventions shape 21st-century skills development primarily through positive shifts in student perceptions. These findings confirm the theoretical expectation that psychological engagement and cultural connection serve as critical drivers in translating innovative learning resources into meaningful skill acquisition.

5. Discussion

The findings of this study offer compelling empirical evidence on the efficacy of interactive ethno-STEM learning materials in promoting students' 21st-century skills, with key mediating roles played by perceived usefulness, cultural relevance, and learning engagement. The structural model revealed that exposure to ethno-STEM materials significantly enhanced students' engagement, sense of cultural connection, and perception of usefulness, all of which in turn positively influenced critical thinking, creativity, collaboration, and communication skills. These results resonate with, but also extend, existing theoretical and empirical discussions in culturally responsive STEM education and the development of 21st-century competencies.

The positive influence of ethno-STEM exposure on perceived usefulness aligns with prior findings that underscore how the perceived value of instructional resources fosters deeper learning involvement (Liesa-Orús et al., 2020; Yusuf et al., 2018). However, this study goes further by demonstrating that usefulness perceptions do not act in isolation but rather intersect meaningfully with students’ engagement and cultural resonance. This triangulated impact is consistent with technology acceptance theory and sociocultural learning perspectives (Gay, 2018; Ryan & Deci, 2020), suggesting that effective instructional materials must be both functionally effective and contextually grounded.

The strong mediating role of cultural relevance, particularly in enhancing creativity, affirms the tenets of culturally responsive pedagogy. Students demonstrated greater creative skill development when learning materials incorporated familiar cultural practices and traditional knowledge a finding consistent with the work of Zakiyah and Sudarmin (2022) and Sumarni and Kadarwati (2020), who emphasized the transformative power of ethnoscience in providing alternative frameworks for problem-solving. Compared to conventional STEM instruction, the ethno-STEM approach appears uniquely capable of providing students with culturally grounded yet intellectually challenging experiences that invite innovative thinking and flexible cognitive engagement (Ardianti & Raida, 2022; Sari et al., 2023). This finding highlights an important theoretical contribution: cultural authenticity should be seen not merely as contextual enrichment, but as a cognitive resource that actively stimulates divergent thinking and creativity.

Learning engagement emerged as the most dominant mediator across all skill domains, particularly for critical thinking, collaboration, and communication. This reinforces earlier studies asserting the central role of student engagement in skill development (Fatmawati et al., 2019; Fredricks et al., 2016; Kwangmuang et al., 2021). The interactive nature of the materials, incorporating digital simulations, hands-on experimentation, and collaborative problem-solving, provided fertile ground for behavioral, emotional, and cognitive involvement, thereby nurturing the kinds of competencies needed for success in 21st-century contexts (Baran et al., 2021; Supena et al., 2021). These results emphasize that instructional design should prioritize conditions that stimulate sustained engagement, supporting future directions toward learner-centered, dialogical, and culturally grounded technology environments.

While previous studies have confirmed the effectiveness of STEM-based instructional materials in improving academic outcomes and higher-order thinking skills (Asrizal et al., 2021; Novitra et al., 2021; Triana et al., 2020), this study contributes a novel theoretical advancement by modeling the indirect mechanisms that explain *how* these outcomes emerge. The demonstration of indirect, rather than direct, pathways constitutes an important theoretical contribution, offering a validated structural model that explains psychological mechanisms connecting cultural pedagogy and 21st-century competencies. This aligns with emerging research that emphasizes learner-centered design and the incorporation of cultural capital in educational innovations (Ciarli et al., 2021; Kamila et al., 2024). Consistent with broader pedagogical research, instructional practices that deliberately align learning tasks with students' cultural contexts can deepen engagement and learning outcomes, underscoring the importance of culturally grounded instructional design in contemporary STEM education (Insorio, 2024; Tanase, 2020).

The minimal direct effects observed between ethno-STEM exposure and the 4Cs also highlight a key implication: instructional innovations do not yield significant skill development through content delivery alone. Rather, the learners' interpretive and affective responses, shaped by perceived utility, cultural congruence, and engagement, are the true drivers of transformation. These findings advance theoretical understandings by supporting a holistic model of learning that integrates pedagogical design, cultural responsiveness, and learner agency.

A key limitation of this research lies in its cross-sectional SEM design, which restricts causal interpretation and relies on self-reported data that may be influenced by subjective bias. Future research should incorporate longitudinal or experimental designs, multimodal engagement tracking, and explore applications across broader cultural settings or digital learning platforms to enhance generalizability and causal depth (e.g., cross-country ethno-STEM comparisons or AI-based adaptive modules).

Ultimately, the unique contribution of this study lies in its synthesis of cultural pedagogy and STEM education through a validated structural model that elucidates the psychological mechanisms underpinning skill development. It provides empirical evidence that culturally embedded, interactive learning materials can meaningfully foster critical 21st-century skills, not by direct transmission, but by enhancing how students perceive, connect with, and engage in learning. These findings not only strengthen theoretical perspectives in STEM education but also provide actionable insights for curriculum designers, educators, and policymakers in developing learning environments that promote equity, enhance student engagement, and support excellence in science education. By modeling psychological mediators, this study advances ethno-STEM research from descriptive effectiveness toward explanatory theory.

6. Conclusion

This study modeled how interactive ethno-STEM learning materials enhance students' 21st-century skills through the mediating effects of learning engagement, perceived usefulness, and cultural relevance. The findings demonstrate that ethno-STEM instruction shapes skill development primarily through students' psychological and affective responses rather than direct instructional transmission, highlighting the importance of culturally grounded and engaging learning environments. Learning engagement emerged as the strongest mediator across most skill domains, reinforcing the critical role of emotional, behavioral, and cognitive involvement in modern science education. Cultural relevance was particularly influential for creativity, emphasizing the value of embedding ethnoscientific knowledge and local cultural narratives to promote innovative thinking. These results provide meaningful implications for curriculum development and policy, encouraging the systematic integration of ethno-STEM frameworks and teacher professional development in culturally diverse contexts. From a broader educational perspective, the study supports the movement toward equitable, context-responsive STEM learning that strengthens both identity and competency. Although the research offers significant insights, its cross-sectional design and limited geographic scope restrict causal generalization.

Future work should utilize longitudinal or experimental approaches and extend the model across diverse cultural and disciplinary settings to assess scalability and sustainability.

Author contributions: The authors contributed to this study in complementary roles. Asrizal, as the corresponding author, was responsible for the conceptualization of the study, development of the methodology, supervision, project administration, and manuscript review and editing. Tho Siew Wei contributed to validation, scholarly review, international academic collaboration, and editorial refinement. Nadila Fathiya was involved in data collection, classroom implementation, instrumentation, and investigation. Fuja Novitra conducted the formal statistical analyses, model interpretation, and data visualization. Helma contributed through data curation, methodological refinement, and validation of instructional materials. Annisa N was responsible for writing the original draft, documentation, and formatting support.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of interest: The authors declared that there were no potential conflicts of interest.

Ethical statement: This study received ethical approval from the Universitas Negeri Padang Research Ethics Committee. Informed consent was obtained from all participating students and their guardians prior to data collection.

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