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Integrating Local Wisdom and Generative AI in Ethno-STEM Materials: A Case Study in Border Education

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Abstract: The Indonesia-Malaysia border region faces educational challenges in the form of limited learning resources, low digital literacy, and lack of pedagogical innovation. This research aims to develop and evaluate generative AI-assisted Ethno-STEM teaching materials based on Dayak and Malay local wisdom to increase student engagement and creativity. The research uses a mixed methods design with a sequential exploratory model. The qualitative phase was carried out through interviews and observations to explore local wisdom, followed by the preparation of Ethno-STEM-based modules with the integration of AI interactive media, and the quantitative phase involved a limited trial of 30 students of class X and 3 science teachers at SMA Negeri 1 Sajingan Besar. The data were analyzed using descriptive statistics and N-gain calculations. The results showed that the modules were positively rated by students, with 87% stating that they agreed or strongly agreed on the aspects of attractiveness, cultural relevance, and ease of use. The improvement in learning outcomes was also significant, indicated by an average N-gain of 0.91 (high category). The recapitulation of student creativity showed achievements in the category of quite creative, with elaboration obtaining the highest score (55.8%). These findings confirm that the integration of Ethno-STEM and generative AI not only improves conceptual understanding, but also fosters students' critical-creative thinking skills, and is worthy of being recommended for schools in border areas.

Keywords: Creativity; Deep learning; Ethno-STEM; Generative AI; Local wisdom

Introduction

The Indonesia-Malaysia border area, particularly in Sambas Regency, West Kalimantan, faces complex educational challenges. Schools around the Aruk Cross Border Post (PLBN) still experience limited access to quality learning resources (Dela & Niron, 2024), low digital literacy (Wicaksono, 2020), and a lack of educators who master innovative pedagogical approaches. A similar condition was also identified at SMA Negeri 1 Sajingan Besar, where the results of interviews with school principals showed that some teachers still had difficulties in implementing deep learning approaches and STEM-based learning. This situation confirms the urgent need for learning innovations that are able to increase student creativity through the integration of educational technology. These findings are in line with research (Jewarut et al., 2024; Meigito et al., 2024; Niken & Nawawi, 2021) that emphasizes the importance of improving digital literacy in the world of education as a foundation for creating a more effective learning process that is relevant to the challenges of the 21st century.

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These conditions show the existence of a gap between the reality of education at the border and the demands of the 21st century paradigm that emphasizes deep, creative, and meaningful learning (Nawawi et al., 2021; Niken & Nawawi, 2021; Prinotama et al., 2019). While national policies encourage technology integration mastery, teachers in 3T areas still face serious obstacles in digital literacy and technology skills mastery. On the other hand, the use of generative artificial intelligence is starting to develop in cities, such as the use of ChatGPT in project-based learning (Araujo et al., 2023; Chiu et al., 2023; Jauhiainen & Guerra, 2023; Sun et al., 2023; Wahdah et al., 2025). However, teachers in border areas often show resistance due to limited competence, concerns related to academic integrity, and lack of contextual support (Dewi & Setyasto, 2024; Ichsan et al., 2023; Zulyusri et al., 2023) . The gap between 21st-century learning needs and the real capacity of teachers in the field underscores the need for AI integration models that are adaptive to local contexts to be more acceptable to educators and students in border schools.

One of the relevant solutions for the context of border education is the Ethno-STEM approach, which is the integration of local and cultural wisdom in science, technology, engineering, and mathematics learning (Dewi et al., 2019; Harris & De Bruin, 2018; Lestari & Rahmawati, 2020; Maulidiyah & Anistyasari, 2020). A number of studies show that ethnoscience-based education can increase student involvement, motivation, and creativity because it provides a contextual learning experience that is close to daily life (Ichsan et al., 2023; Pratiwi & Pujiastuti, 2020; Sunariyati et al., 2018; Susilaningtiyas & Falaq, 2021; Zonasi et al., 2024) . Meanwhile, the conservation practice of Dayak Tembawang customary forests that has taken place in Sajingan Besar sub-district has reflected the principles of sustainable ecology which is in line with the topic of ecosystems in biology and can be used as meaningful project-based teaching materials. By linking modern science and traditional knowledge, Ethno-STEM has been shown to enhance innovative and creative thinking skills, deepen understanding of science and technology concepts, while strengthening students' cultural identities (Hamidah et al., 2025; Septina et al., 2025; Wijayanti et al., 2025).

In line with Ethno-STEM values that emphasize cultural contextualization, the development of artificial intelligence, particularly generative AI, opens up new opportunities in science learning. This deep learning-based AI technology can be used to provide interactive content, facilitate personalization of learning, and support teachers in designing creative teaching media (Dewi & Setyasto, 2024; Mutambara & Bayaga, 2021; Zulyusri et al., 2023). A systematic review conducted (Purnama et al., 2023) on the integration of ChatGPT in Project Based Learning also confirms the potential of AI in assisting students in the process of investigation and problem-solving. However, a number of studies have reported resistance or concern to the use of AI in education, both related to the authenticity of students' work and ethical aspects (Adams et al., 2023; Akgun & Greenhow, 2022; Sevnarayan & Potter, 2024). On the other hand, ethnoscience research has more highlighted the integration of local cultures in science curricula without involving cutting-edge technology (Hidayah et al., 2024; Qomaria & Wulandari, 2022; Sumarni & Kadarwati, 2020). Thus, until now there has been no study that explicitly combines Ethno-STEM approaches with generative AI in the context of Indonesia-Malaysia border schools. This confirms the novelty of this research, which seeks to synergize the local wisdom of the Malay and Dayak communities with smart technology to present a learning model that is adaptive to the digital era while being relevant to the culture of the Indonesian-Malaysian border communities.

This research seeks to fill this gap by utilizing generative AI-assisted Ethno-STEM teaching materials that have been developed and rooted in the local wisdom of the Malay and Dayak Communities in the Border Area. The main focus of this research is: (1) identifying the characteristics and potentials of local cultures that can be integrated into science learning; (2) evaluate the perception of teachers and students on the attractiveness, cultural relevance, and contribution of the Generative AI integrated Ethno STEM teaching materials in developing creativity skills. The practical contribution of the research is to provide an alternative to contextual innovative teaching materials for schools in the 3T region; While theoretically, it can expand the literature on ethno-pedagogical synergy and artificial intelligence technology in science education. Thus, this research affirms novelty through an integrative approach that connects traditional knowledge with artificial intelligence to present a learning experience that is culturally relevant while being adaptive to the demands of the digital age.

Method

This study uses a mixed methods approach with a sequential exploratory design (Creswell, 2013; Meissner et al., 2011). This design begins with a qualitative phase to explore local wisdom, followed by the development of Ethno-STEM teaching materials assisted by generative AI, and ends with a quantitative evaluation to assess the perception of teachers, students, and the impact of teaching materials on student creativity.

Qualitative Phase (Exploration of Local Wisdom), exploration was carried out in Sajingan Besar District,

Sambas Regency, West Kalimantan. Data were collected through in-depth interviews, participatory observations, and documentation studies. The informants include school principals, senior teachers, traditional Dayak and Malay leaders, as well as local residents who understand the local culture. The focus of the excavation is cultural practices and traditional knowledge relevant to the learning of Biology, particularly the topic of ecosystems and biodiversity. The data was analyzed by thematic coding to identify the characteristics and potential of local wisdom. Triangulation of sources is used to maintain legitimacy.

The Teaching Material Prototype Preparation Phase, carried out after the qualitative phase which is used as the basis for the preparation of Ethno-STEM teaching material prototypes for high school Biology subjects. The teaching materials are in the form of modules on ecosystem and biodiversity topics, equipped with illustration media, simulations, and interactive content which are partly developed with the help of Generative AI and adapted to the Independent Curriculum. Partner teachers act as validators of content and feasibility, while students become the main users of the module.

Quantitative Phase (Evaluation of the use of teaching materials). At this stage, the trial was carried out at SMA Negeri 1 Sajingan Besar involving 30 students in class X and 3 science teachers (Biology, Chemistry, Physics), taking into consideration the geographical conditions of the border, the limitations of accompanying teachers, and the research time that made a small-scale research design to be applied as a small-scale trial class. Meanwhile, the role of science teachers is to provide content validation, guide the application of modules, and provide insight into the applicability of teaching materials. Meanwhile, in the measurement of student and teacher perception, a questionnaire with a Likert scale was carried out (aspects: attractiveness, cultural relevance, ease of use). Meanwhile, student creativity is measured through the product assessment rubric of project assignments (creating Ecosystem designs using Canva AI), as well as creativity tests that include indicators of idea originality, flexibility, elaboration, and ability to connect concepts. Assessment was carried out before and after the intervention (pre-test and post-test).

Qualitative data analysisis carried out through reduction, thematic categorization, and descriptive interpretation. Quantitative data were analyzed with descriptive statistics (mean, standard deviation) to describe perceptions, as well as N-gain calculations to see the effectiveness of teaching materials in increasing students' creativity. The results of both phases were then integrated to answer the research questions.

Result and Discussion

Characteristics of Local Wisdom Integrated in Ethno-STEM

The results of qualitative exploration revealed three main elements of local wisdom in border communities in Sambas Regency that are relevant to Biology material and have the potential to be integrated in Ethno-STEM learning, namely: customary forests, shifting farm practices, and the use of traditional medicinal plants. The findings of this study are in line with (Sevnarayan & Potter, 2024) the statement that the Tembawang forest is a communally managed Dayak community forest, containing a variety of fruit trees and forest plants with economic and ecological value. Meanwhile, based on the results of interviews with teachers at SMA Negeri 1 Sajingan Besar, it is known that customary forests are forests that have been inherited from generation to generation as a "granary" of biodiversity and community food reserves, and are located near residential areas.

A unique characteristic of customary forests is the agroforestry system based on local wisdom, where after the fields are not productive to produce rice, they will be abandoned, and planted with fruit trees (durian, tengkawang, rubber and others). Furthermore, the community in Sajingan sub-district will allow the fields to regenerate naturally, thus forming a species-rich forest again.

The majority of the people in Sajingan District, Sambas Regency are the Dayak and Malay tribes, who have long practiced traditional knowledge, especially about forest ecosystems and natural resources. The practice of traditional knowledge or local wisdom is relevant to be associated with the topic of ecosystems and biodiversity in high school Biology learning in class X. So the researcher asked 3 teachers to teach Science subjects (Biology, Physics and Chemistry) to provide input and suggestions on the Generative AI-Assisted Ethno-STEM teaching materials that have been created.

Figure 1. Science Teachers at SMAN 1 Sajingan Besar are reviewing ethno-STEM teaching materials assisted by generative AI (Personal Documentation, 2025)

The following three main aspects discussed in the teaching materials can be explained as follows; First, traditional conservation (Tembawang), where the Dayak Tribe in West Kalimantan has known the Tembawang Forest as a customary forest managed with strict customary rules. The local community prohibits tree felling, forest burning, and hunting in the Tembawan area, so that the forest ecosystem remains sustainable (Fera et al., 2024). Meanwhile, the implementation of customary rules for the Dayak community in the Aruk Border ensures the sustainability of natural ecological succession. Where the former field land is no longer productive, it will then be allowed to grow into a secondary forest with various types of fruit-producing trees, rattan, bamboo, and medicinal plants (Seli et al., 2021; Septiani, 2025). The activities carried out by the Dayak indigenous people on the Indonesia-Malaysia border have reflected the in situ conservation of the genetic diversity of plants and fauna through the implementation of customary policies. As stated in conservation studies, biodiversity damage is often caused by environmental degradation (Putra Ramadhan, 2025), so it is necessary to integrate local wisdom to improve students creative thingking skills (Sari & Suryani, 2025). Thus, the Tembawang customary forest can function as a natural laboratory to understand the concept of ecosystem, succession, and the role of humans in environmental conservation, because customary practices underlie forest conservation activities.

Second, the shifting farm system (shifting cultivation), where the Dayak people practice the shifting farm system ("Bauma Tahutn" which is sometimes written "Bauma Batahutn") in the tradition of the Dayak Kanayatn community (Bahri et al., 2018). Where farm activities move, it is highly integrated with local ecological knowledge (Fera et al., 2024). In this system, farmers open land with local wisdom to plant rice and corn, but after the planting period and the land is not productive, the land is abandoned for several years so that the soil regenerates. Farmers have a deep understanding of the soil fertility cycle and the selection of suitable crops after logging, as well as the custom of clearing land with controlled fires so that later burned wood can be used naturally to fertilize the soil (Jalil et al., 2023). In other words, the practice of shifting fields describes sustainable land use where communities do not destroy forests, but comply with customary rules to restore the natural cycle so that ecosystem productivity recovers.

Traditional medicinal plants are one of the important local wisdom of the Malay and Dayak communities in the border area. This ethnobotanical knowledge has been passed down from generation to generation, including the use of local flora such as the root of the earth peg (Eurycoma longifolia) for stamina, sungkai leaves as a fever reducer, and doorang bark as an antiseptic. The integration of this knowledge in Biology learning is very potential, especially in plant structure and function materials, secondary metabolites, and basic health. Through simple projects, identification of active compounds, plant extraction, and antibacterial activity test students not only practice science process skills, but also learn to develop creativity through the innovation of tradition based products, such as herbal teas or natural ointments.

The integration of ethnobotany in Ethno STEM has contextual, empirical, and holistic value that is able to bridge modern scientific knowledge with local traditions. This approach makes science more meaningful because it is rooted in the cultural reality of students while supporting the preservation of knowledge that is beginning to be eroded by the younger generation. These findings are in line with the concept of techno-vernacular creativity (Doyan et al., 2023; Gaskins, 2021), which emphasizes that creativity grows when education and technology are rooted in culture. Thus, Ethno-STEM in border areas can be an effective strategy to foster students' critical-creative thinking skills in solving real community problems, both in the fields of agriculture, health, and the environment.

The results of the study show that the use of Ethno-STEM teaching materials assisted by Generative AI is able to increase students' creativity in border areas. The percentage of achievement before intervention was relatively low, but after intervention there was a significant improvement in almost all indicators.

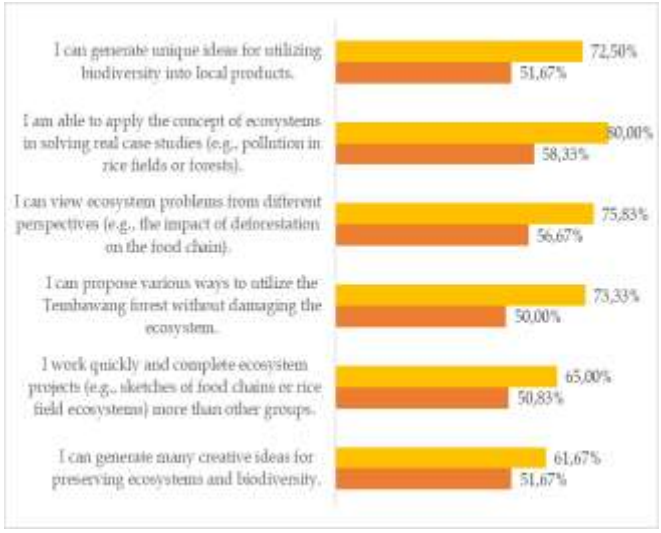

Figure 2. Creativity questionnaire results

Figure 2 shows that the ability to apply the concept of ecosystems to real cases increased from 58.33% to 80.00%, and seeing ecosystem problems from various perspectives increased from 56.67% to 75.83%. The

highest increase occurred in the indicator proposing the use of the Tembawang forest without damaging the ecosystem (50.00% to 73.33%), which emphasized the role of local wisdom as a meaningful learning context. These results are in line with the findings that the integration of local wisdom in STEM can strengthen cultural relevance and learning motivation, as well as increase student creativity (Widyana et al., 2023). The support of AI technology also enriches contextual and innovative learning experiences (Cheng et al., 2020), while the application of local wisdom-based models has proven effective in 3T areas. Thus, these innovations can be an important strategy to improve 21st century skills while preserving local culture.

The project based Ethno STEM approach carried out in this study can be seen in figure 3. Where the researcher combines the exploration of local ecology with the use of artificial intelligence technology. The syntax is designed to guide students gradually in understanding the concept of ecosystem through the perspective of the local culture of the Sambas Regency Community, especially those in the Aruk Border, to develop students' creativity through the preparation of AI prompts, to produce a visualization of future ecosystems that reflect sustainability values. This approach not only integrates science, technology, and cultural wisdom, but also fosters students' emotional and reflective engagement in a contextual and transformative learning process.

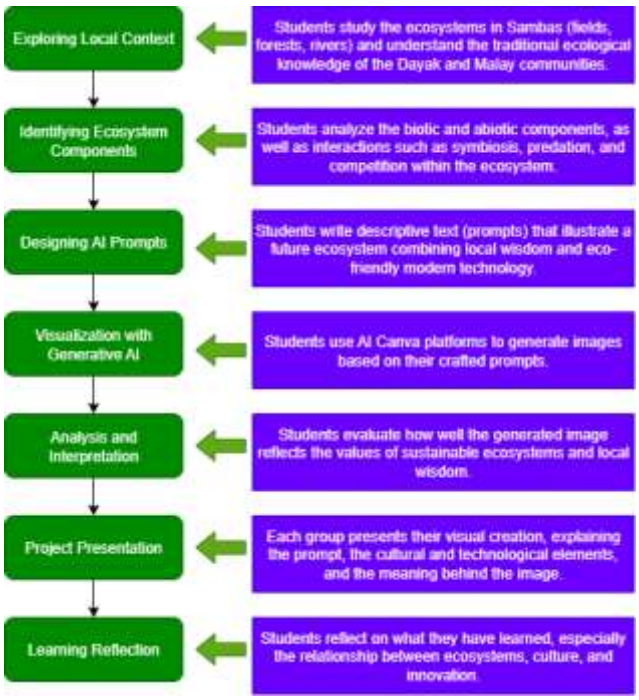

Figure 3. Syntax of the ethno-STEM approach

The Ethno-STEM syntax in figure 3, reflects the principles of contextual and holistic learning, in which students become not only recipients of knowledge, but also active creators. The steps start from concrete local understanding (context exploration), continue with scientific analysis (component identification), then processed through technology (AI prompts and visualization), and end with meaning and reflection. This process strengthens the connection between modern science and local wisdom, and instills the value of sustainability, creativity, and collaboration. This approach is also in line with the principle of Merdeka Belajar which emphasizes meaningful and transformative learning. The prompts used by students to produce ecosystem images in Group 1 (Conservation Focus) are as follows; "Lush and diverse tropical forests in Sambas, West Kalimantan. In the middle, there is a traditional Dayak longhouse made of sustainable wood. The forest is a 'sacred forest' (sacred forest) protected by local wisdom, with crystal clear rivers and a variety of native animals such as hornbills and orangutans that live in peace. The image should be photorealistic, showing a harmonious balance between nature and culture, with bright green colors". While the images produced by students can be seen in figure 4.

Figure 4. Prompt results using Canva AI

Teachers' and Students' Perceptions of AI-Assisted Ethno-STEM Teaching Materials

After the implementation of learning using Ethno-STEM modules assisted by Generative AI, then the perception of teachers and students towards the teaching materials was evaluated through a questionnaire. In general, responses from both groups of users showed a very positive response. From the student side (N=30), the questionnaire analysis showed that 87% of students agreed that the module was interesting and made them more enthusiastic about learning Biology. Meanwhile, from the teacher's side, although the number of respondents was small (N=3, namely Biology, Physics and Chemistry teachers), valuable qualitative insights were obtained. The three teachers expressed satisfaction with the teaching materials developed. They give a positive assessment on the aspects of readability and relevance. The Biology teacher

assessed the module "very helpful in explaining abstract concepts through local concrete examples". According to him, usually students have difficulty understanding ecological material because the examples in textbooks are far from their environment, but with the context of the Tembawang forest and the shifting fields that students are familiar with, the class discussions became more lively. Teachers also appreciated the integration of AI to visualize forests, rice fields, and other ecosystems because of the difficulty in learning. Although teachers initially felt hesitant about the use of AI, because they had never used it before, after trying, teachers felt the benefits in provoking students' curiosity. One teacher said, "This module opens up new insights that AI can be used to elevate local culture in learning" – something she had never thought of before. This indicates a change in teachers' perception towards being more open to technology. This teacher's response is interesting when compared to studies Watermeyer et al. (2024) that found academic resistance to AI. Our research findings suggest that when teachers are engaged in the use of AI that is contextual and culturally relevant to students, such resistance can be reduced. Teachers see AI not as a threat, but as a tool that can be controlled and directed according to material needs.

The obstacles noted by teachers are technical problems such as the limitation of ICT infrastructure in border schools. Unstable internet access had hampered the function of the AI chatbot in the module in several sessions. However, this is overcome by providing an offline mode. Teachers recommend improving ICT facilities in schools so that innovations like this can be sustainable. From the cultural aspect, the teacher also suggested that the content of local wisdom be expanded to include Malay culture such as besaprah and plain flour. The results of this study show that teachers are enthusiastic about integrating more local elements to make learning richer. Overall, user perceptions conclude that this AI-assisted Ethno-STEM module is feasible and effective to use. The high attractiveness and relevance of the module in the eyes of students is in line with the findings of Priyani et al. (2020) who succeeded in improving the science process skills of border students through ethnoscience-based learning. The difference is that our innovations add an AI dimension, so it is expected to provide added value in terms of interactivity and information coverage. Research by Kasun et al. (2024) emphasizes the importance of making AI accessible to marginalized youth to drive educational inclusion. The results of this study prove that AI can be adapted to marginal contexts (rural border schools) and actually strengthens local wisdom instead of displacing it. This is an important contribution: showing a model of synergy between advanced technology and local wisdom in a real educational setting.

Attractiveness, Relevance, and Impact of Teaching Materials on Creativity

The results of the assessment show that generative AI-based Ethno-STEM teaching materials are considered interesting and relevant by students, so that they are able to increase student involvement in the learning process. This increase in attractiveness and relevance has a direct impact on the development of creativity, as reflected in the results of pretest and posttest measurements summarized in Table 1.

Table 1. Summary of Student N-Gain Calculation Results

N-Gain Category	Score Range	Number of Students	Percentage
Tall	0.75 – 1.00	29	96.7%
Keep	0.34 – 0.74	0	0.0%
Low	≤ 0.33	1	3.3%

Based on Table 1, as many as 29 students (96.7%) reached the high category with an N-Gain score of 0.75–1.00, while only 1 student (3.3%) was in the low category. The overall average N-Gain was 0.91 which belongs to the high category, indicating that generative AI-assisted Ethno-STEM teaching materials are effective in boosting students' creativity. Meanwhile, the results of Shiwa's perception of Ethno-STEM teaching materials assisted by generative AI can be seen in table 2.

Table 2. Students' Perception of Ethno-STEM Modules with Generative AI Assisted

Assessment Aspects	Agree & Strongly Agree	Neutral	Disagree
Learning appeal	26 Students (86.7%)	3 (10%)	1 (3.3%)
Relevance to culture	27 Students (90.0%)	2 (6.7%)	1 (3.3%)
Ease of use	25 Students (83.3%)	4 (13.3%)	1 (3.3%)
Overall average			87% - positive

Based on Table 2, most students rated the modules as interesting and relevant, with 87% stating that they agreed or strongly agreed on aspects of attractiveness, cultural relevance, and ease of use. These results show that the modules are not only culturally contextual, but also well received by students in border schools.

The high appeal of learning is reflected in the enthusiasm of students during implementation. Students are more active in asking questions and discussing when material is related to their own environment. This creates a collaborative and exploratory learning environment. According to the teaching teacher, usually only 20-30% of students are active during conventional class discussions, but in this module-based discussion participation increases, almost

all students want to contribute. This active engagement is an important foundation for critical and creative thinking, as students are encouraged to ask questions, put forward ideas, and challenge assumptions. The educational literature mentions that interest and motivation for learning are positively correlated with higher-level thinking skills: when students are interested in a topic, they will explore and analyze more deeply. The case in our class supports this; The high appeal of the module encourages students to study more actively and think more deeply.

Table 3. Recapitulation of Student Creativity Percentage

Indicators	Average Score	Percentage	Category*
Fluency	2.07	51.7%	Quite Creative
Originality	2.07	51.7%	Quite Creative
Flexibility	2.03	50.8%	Quite Creative
Elaboration	2.23	55.8%	Quite Creative – Approaching Creative

Furthermore, on student creativity, this module provides space for students to be creative and imaginative with the local context. The results of the recapitulation show that student creativity in the four indicators is still in the category of quite creative. The elaboration indicator obtained the highest achievement percentage of 55.8%, which means that students are relatively able to develop ideas in more detail and detail when completing assignments. On the other hand, the flexibility indicator occupies the lowest position with an achievement of 50.8%, indicating that students are still limited in seeing a problem from various perspectives or producing a variety of solutions. The other two indicators, namely fluency and originality, each achieved 51.7%, showing that the smoothness of producing ideas and the ability to produce unique ideas still need to be improved. Overall, achievements that are in the category of quite creative indicate that students already have the potential for creativity, but more innovative and contextual learning interventions are still needed so that their creativity can develop towards a higher category, namely creative or very creative.

The findings regarding increased creativity are consistent with research (Sudarmin et al., 2020) in which Ethno-STEM learning (in the context of chemical batik) improves students' creative skills through innovative product design. Meanwhile, the combination of ethnoscience, STEM, AI and project approaches has been shown to have a positive effect on the creativity of students from diverse backgrounds. What makes our model unique is the addition of Generative AI as a catalyst. AI plays a role in providing inspiration and additional information that enriches students' ideas. For example, when students design digital posters about Tembawang conservation, they use AI-based applications to create aesthetically pleasing forest illustrations. This sparks their imagination and motivates them to produce the best work possible. In terms of creative thinking, AI can act as a creative partner that provides a variety of examples or visuals so that students get new insights. From the perspective of creativity theory, it supports the idea that human-AI collaboration can improve creativity outcomes (AI offers generative ideas, humans select and modify according to context). Of course, it should be noted that teachers should direct the use of AI to stay on the educational corridor.

Overall, the improvement of students' critical thinking skills and creativity in this border classroom shows that efforts to integrate local wisdom and AI technology in learning not only improve understanding, but also foster higher-order thinking skills. This has far-reaching implications. First, students in the 3T area are proven to be able to achieve high 21st century competence if they are provided with contextual and quality learning facilitation. Second, this approach can reduce the gap in education quality between centers and remote areas, as AI technology can bridge limited access to information, while local wisdom ensures that materials remain relevant and easy to understand. Third, this learning model is in line with the Merdeka Learning agenda which encourages project-based curriculum innovation and the character of Pancasila student profiles (faith, global diversity, mutual cooperation, creativity, independence, critical reasoning). Students learn science while appreciating their culture, and are open to modern technology – an ideal combination of competencies in the era of the Industrial Revolution 4.0.

Conclusion

This study has succeeded in showing that the development and implementation of Generative AI-assisted Ethno-STEM teaching materials rooted in the local wisdom of the Malay and Dayak communities in the Indonesia-Malaysia border area can be an innovative solution in improving the quality of Biology learning, especially on the topic of ecosystems and biodiversity. First, in terms of attractiveness, relevance, and suitability of teaching materials, the results of the questionnaire showed that the majority of students rated this module positively, with an average of 87% of respondents stating that they agreed or strongly agreed that the module was interesting, relevant to the local culture, and easy to use. Science teachers also give appreciation, because the modules facilitate the delivery of abstract concepts through a cultural context that is close to students' lives. Second, from the aspect of learning

effectiveness, the results of the N-Gain calculation showed an average score of 0.91 (high category), with 96.7% of students in the high improvement category. This confirms that the module is effective in improving student learning outcomes. Third, from the aspect of developing students' creativity, the recapitulation shows the average achievement in the category of quite creative with details: fluency 51.7%, originality 51.7%, flexibility 50.8%, and elaboration 55.8%. Although still at a fairly creative level, the intervention of this module encourages significant improvements, especially in the elaboration aspect, as well as shows the role of Generative AI as a catalyst that enriches ideas, facilitates visualization, and triggers the originality of students' ideas. Overall, the study confirms that the integration of Ethno-STEM and generative AI not only strengthens cultural relevance in science learning in border schools, but also effectively improves learning outcomes and develops students' creative skills. These findings have important implications for the development of teaching materials in the 3T region, as they show that even students in remote areas are able to achieve 21st century competencies when facilitated with contextual, adaptive, and innovative learning.

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Author Contributions

Conceptualization, Nawawi and Syafrial Nur; methodology, Nawawi; software, Arif Januardi; Shawn Scott, Shawn and Shawn Scott; formal analysis, Syafrial Nur; Scott, Scott; resources, Arif Januardi; data curation, Moad; writing—original draft preparation, Nawawi; writing—review and editing, Syafrial Nur and Arif Januardi; visualization, Moad; Scott, Scott; project administration, Nawawi. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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