International Conference on Biology Education, Natural Science, and Technology
Vol. 3 No. 1 (2025)
E-ISSN : 3026-5428

Designing a Generative STEM Model Based on Subak Landscape: Integrating Entropic Modulation and Indigenous Ecological Knowledge into Science Education

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KEYWORDS:
Generative STEM; Subak system; Entropic modulation; Indigenous ecological knowledge; Science education

ABSTRACT

This study introduces and evaluates a generative STEM education model grounded in the Subak landscape of Bali, designed to integrate Indigenous ecological knowledge with contemporary science learning frameworks. The model draws on the principles of *generative justice*—defined as value circulation within communities—and *entropic modulation*—a concept referring to balancing variation and structure for resilience. Culturally Situated Design Tools (CSDTs), which are simulation-based tools for visualizing ecological processes, were employed to model sustainable farming practices in Subak, focusing on intermittent irrigation data that connects water surface levels, drying periods, drying duration, and timing with changes in temperature, methane emissions, and rice yield. A mixed-methods approach was applied, combining design-based research, participatory action research, classroom observations, focus groups, and pre/post assessments. Preliminary findings indicate a 27% improvement in students' conceptual understanding, particularly regarding Subak water management, greenhouse gas emissions, and the relationships between irrigation practices, environmental conditions, and rice production. These findings demonstrate that the Subak-based generative STEM model not only enhances student engagement, systems thinking, and ecological literacy but also offers concrete evidence for developing a culturally grounded framework for decolonizing STEM education.

1. INTRODUCTION

1.1. Background and Context

Mainstream STEM education in post-colonial settings remains heavily influenced by Eurocentric paradigms that emphasize abstraction, universality, and linear logic, often rendering science less relevant to the cultural and ecological contexts of learners (Jin, 2021; Jones & Donaldson, 2021). This lack of contextualization reduces student engagement and marginalizes Indigenous knowledge systems that could enhance inclusivity and enrich learning outcomes (Alexiades et al., 2021; Rioux & Smith, 2019).

Culturally responsive pedagogies address this gap by embedding local epistemologies into science curricula, fostering greater relevance and participation (Photo & McKnight, 2024). Studies show that integrating Indigenous perspectives into STEM not only improves retention and academic performance among diverse learners but also promotes deeper engagement and scientific literacy (Tapia et al., 2017; Gay, 2013; Simpson et al., 2023). Yet, many existing STEM programs still lack direct integration with local agroecological practices, which could serve as authentic, data-rich laboratories for systems thinking and environmental awareness. These developments highlight the urgent need to shift from extractive, decontextualized STEM models toward inclusive, culturally grounded frameworks that reflect the pluralistic nature of scientific knowledge (Marosi et al., 2021).

One of the core challenges lies in the dominance of conventional STEM approaches that prioritize standardization and efficiency over local context and sustainability. This mirrors patterns of knowledge extraction that often exclude community-based ecological practices. Such tendencies not only diminish the cultural grounding of science education but also reinforce unsustainable relationships with nature and society. Given the growing implications of STEM practices in global crises—such as climate change, biodiversity loss, and social inequity—there is an increasing demand for STEM models that are inclusive, ethically oriented, and ecologically grounded.

At the same time, culturally inclusive and ethically grounded STEM must maintain the same understanding of scientific rigor: falsifiable, empirically tested hypotheses, statistical analysis of data, peer review, and replication of results in the professional community. This balance is especially important in the current era, as public confidence in science declines while misinformation and conspiracy theories about vaccination, climate change, and other critical issues are accelerating (Mills & St Clare, 2025).

The generative STEM framework emerged from this synthesis between rigorous scientific standards and decolonial frameworks that re-center community knowledge, dismantle epistemic hierarchies, and integrate pluralistic ways of knowing into formal education (Eglash et al., 2019; 2020). Generative STEM is built upon three principles: (1) distinguishing value-circulating Indigenous systems from value-extracting industrial systems; (2) creating meaningful translations of Indigenous practices into modern STEM contexts; and (3) returning educational value to the originating communities. For example, Subak's democratic water management and crop rotation practices have been transformed into computational simulations (CSDTs) that model how intermittent irrigation affects temperature, methane emissions, and rice yield. These perspectives validate the role of Traditional Ecological Knowledge (TEK) in enhancing the relevance of science education (Alexiades et al., 2021).

1.2. Research Problem and Rationale

Although Indigenous ecological knowledge is increasingly valued, its integration into formal science education remains limited. Curricula often treat systems like Subak as cultural artifacts rather than living, data-rich ecological practices. This creates a disconnect between classroom science and the lived realities of Indigenous and rural students, leading to reduced engagement and upholding Western-centric, decontextualized STEM models. Recent research shows that aligning curricula with Indigenous knowledge fosters inclusivity and improves students' connection to their environment (Jin, 2021; Morris et al., 2019). Preliminary findings from this study's pre/post assessments already demonstrate measurable gains in student understanding (27% increase), highlighting the importance of integrating Subak's dynamic irrigation and environmental monitoring practices into STEM learning.

The Subak system in Bali—characterized by democratic water governance, ecological feedback loops, and cultural integration—offers a powerful yet underutilized model for STEM education. This study applies a generative STEM framework built on Subak's principles of entropic modulation, biodiversity, and community-based decision-making (Suasih et al., 2024; Ardana et al., 2024). By using simulations derived from intermittent irrigation data (water level fluctuations, drying periods, and environmental variables such as methane emissions and temperature), the model links traditional ecological knowledge with modern computational tools. This integration deepens ecological understanding, cultural relevance, and student engagement (Sardiana & Wiguna, 2023).

1.3. Objectives and Scope

This research aims to design, implement, and evaluate a generative STEM education model that integrates Subak's ecological and cultural logic with inquiry-based science learning. To ensure broad access, the developed simulations and tools are hosted on the Culturally Situated Design Tools platform (https://csdt.org/culture/bali/index.html). The scope of this study includes curriculum design, development of computational prototypes based on real Subak farming data (e.g., water levels, drying cycles, methane emissions, and rice yield), and pilot implementation at the secondary school level. Empirical evidence from preliminary assessments highlights that integrating Indigenous ecological knowledge into STEM not only enhances pedagogical relevance but also improves students' conceptual understanding and engagement (Zen et al., 2024; Lansing et al., 2023).

1.4. THEORETICAL FRAMEWORK

1.4.1. Generative Justice and STEM

Generative justice provides a conceptual foundation for transforming educational systems from value-extraction models to those emphasizing value circulation and community empowerment. It prioritizes local knowledge and equitable participation. Generative justice has been applied to diverse social issues, including architecture (Lokko and Eglash, 2017), economy (Robinson et al., 2025), and prison reform (Perrin, 2025). In the context of STEM education, this paradigm critiques conventional industrial logics that often displace knowledge and resources from source communities without reciprocal benefits. Dawson et al. (2024) emphasize the necessity of equitable pedagogies in informal science learning, highlighting education's role in advancing community empowerment

Thus, the generative STEM framework promotes locally grounded learning systems that are inclusive, reciprocal, and adaptive. Gallay et al. (2021) demonstrate how place-based STEM education can enhance students' sense of agency by linking learning to community needs. Within this framework, pedagogical strategies are designed to integrate cultural and ecological contexts with STEM practices, particularly those informed by Indigenous knowledge systems. By synthesizing these perspectives, the approach not only diversifies curricula but also fosters co-constructed, community-driven knowledge creation, aligning education with social equity and ecological sustainability.

The conceptual differences between extractive and generative models of STEM are summarized in Table 1, which highlights how Subak-inspired generative STEM emphasizes cultural relevance, participatory learning, and ecological reciprocity compared to conventional extractive approaches.

Table 1. Key differences between the extractive stem and the generative STEM approach based on the Subak system

Core Concept	Extractive STEM	Generative Subak STEM
Goal	Efficiency, standardization, control	Diversity, sustainability, shared responsibility
Knowledge Context	Universals as synonymous with decontextual	Universals contextualized within local ecology and culture
Power Structure	Top–down, colonial-industrial logic	Bottom–up, participatory, generative justice
Learner Role	Passive consumers	Active co-creators
Cultural Relevance	Ignores traditional wisdom	Rooted in *Tri Hita Karana* and Subak rituals
Nature Relationship	Exploitative, instrumental	Reciprocal, regenerative

Core Concept	Extractive STEM	Generative Subak STEM
Curriculum Design	Centralized, uniform	Locally designed, context-driven
Technology Use	Detached from lived reality	Grounded in local ecosystems (sensors, simulations)

1.4.2. *Entropic Modulation in Ecology and Computation*

Entropy, as a scientific concept, denotes the degree of disorder or unpredictability in a system. In ecological contexts, higher entropy is linked to biodiversity and resilience, while lower entropy indicates uniformity and fragility (Roach, 2020; Quijano & Lin, 2014). Eglash et al. (2023, 2024a) introduced the term "entropic modulation" to refer to traditional and Indigenous practices that balance variability and structure to maintain productivity, adaptability, and sustainability across dynamic environments. They note that entropic modulation is a systemic feature of natural systems at many levels. In evolution, for example, genotype provides a predictable, regular structure, while phenotype's complexity allows an exploration of environmental success. In animal behavior, organisms vary between regularized movements and exploratory actions such as hunting. Eglash et al. (2024b) extend the entropic modulation concept to artificial intelligence, in which systems use transformations over a high entropy data base to produce low entropy prompt responses.

In this study, the term is applied pedagogically to describe how variation and structure are intentionally balanced to support adaptive thinking and resilience. Flexible learning pathways combined with structured reflection can create resilient educational outcomes. That requires learning environments designed to reflect complexity, variation, and iterative problem-solving (Vranken et al., 2014; Cushman, 2018).

Applied to education, particularly within this study's Subak-based generative STEM model, entropic modulation guides the structuring of learning as a dynamic, locally rooted system. Students alternate between high-entropy phases (e.g., creative inquiry, design-based activities, hypothesis generation) and low-entropy phases (structured exercises for concept consolidation and assessment). This balanced approach encourages learners to integrate scientific knowledge with cultural insights while building systems thinking skills necessary to address contemporary environmental and social challenges.

1.4.3. *Subak as a Generative Ecological Model*

The Subak system of Bali exemplifies a generative ecological model that integrates ecological management with community-based governance. Designated by UNESCO as a cultural heritage system, Subak is a centuries-old, collaboratively managed irrigation network structured through nested governance layers, enabling synchronized water cycles that support equitable distribution, pest control, and biodiversity—key indicators of ecological resilience (Ardana et al., 2024; Achmadi et al., 2023).

Its strength lies in sustaining ecological diversity through collective coordination, reinforcing principles of sustainability. More than a technical infrastructure, Subak is deeply rooted in the Tri Hita Karana philosophy, which promotes harmony among humans, nature, and the divine, embedding ethical and spiritual values in environmental stewardship (Prastyadewi et al., 2021). This socio-hydrological system demonstrates how ecological function, cultural meaning, and democratic participation operate in synergy, offering an exemplary model for integrating cultural narratives into STEM education.

The visual model in Figure 1 synthesizes the foundational components of the generative STEM framework developed in this study. Central to this model is the principle of Generative STEM, supported by four interdependent domains: entropic modulation, systems thinking, indigenous knowledge, and biodiversity. Each element not only reflects a core pedagogical or epistemological pillar but also illustrates the dynamic interconnectivity required for sustainable science education.

At the periphery, the label “Based on Subak Landscape” emphasizes the rootedness of the model in the ecological and cultural logic of Bali’s traditional irrigation system.

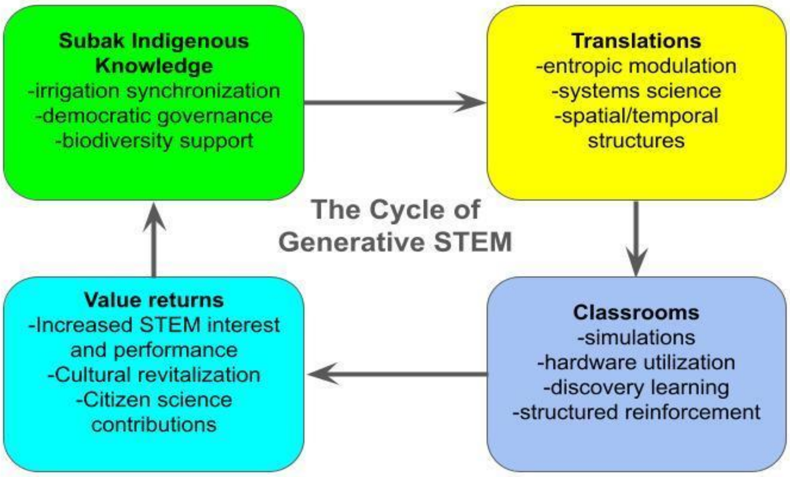


Figure 1. Conceptual Integration of Generative STEM Based on the Subak Landscape

2. MATERIALS AND METHODS

2.1. Research Design

This study employs a mixed-methods design combining qualitative and quantitative approaches, integrating Design-Based Research (DBR) cycles and Participatory Action Research (PAR) phases to develop a generative STEM model grounded in the Subak landscape. DBR supports the iterative design, prototyping, and testing of context-sensitive tools, while PAR ensures that teachers, students, and community members co-create content and provide feedback at every stage.

The design process included three structured cycles of workshops with international experts, lecturers, student teachers, local teachers, and students. From June 2–5, 2025, a series of collaborative workshops at one university and one middle school led to the co-design of CSDTs content based on sustainable farming practices and Subak irrigation logic. Subsequently, an in-depth discussion was conducted with a researcher, whose expertise lies in sustainable rice field management that integrates the optimization of water volume, the application of modern agricultural technologies, the mitigation of methane emissions, and the enhancement of rice productivity.

This collaboration informed the DBR refinement phase, resulting in a conceptual framework that was translated into a CSDTs-based simulation model. This model served as a preliminary study, offering an interactive platform for understanding how strategic water management and technological interventions can simultaneously support environmental sustainability and agricultural efficiency.The outcomes of this collaboration were subsequently tested during the preliminary trial conducted on July 15-16 with 26 pre-service teachers. Their engagement with the simulation model, combined with pre- and post-assessments, demonstrated significant improvements in conceptual understanding, particularly concerning the relationships among water management, methane emissions, and rice productivity.

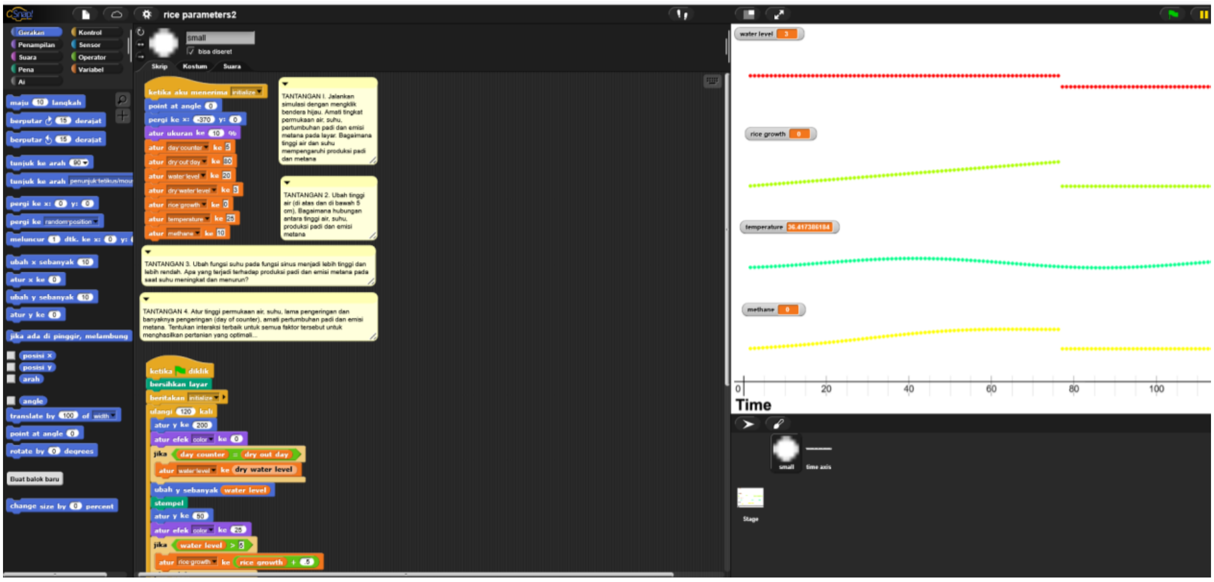
2.2. Participants and Setting

The study takes place in Bali, Indonesia, involving pre-service science teachers, secondary school students, and local community members in schools near the Subak irrigation network. Collaborative activities with international experts and local educators were central to identifying culturally relevant simulation topics, such as intermittent irrigation, predator-prey dynamics, and environmental feedback. The participants include 5 lecturers, 26 pre-service teachers, 6 local teachers, 26 students, 1 agricultural expert, and 2 international collaborators. All participants were provided with clear information about the research purpose and procedures and gave informed consent to voluntarily participate in the study, in accordance with ethical research standards. These joint sessions ensure that the curriculum and simulation models reflect both the scientific and cultural aspects of Subak practices.

2.3. Learning Interventions.

The learning interventions were structured into three stages: (1) conceptual introduction to Indigenous knowledge of Subak irrigation and ecology; (2) collaborative exploration through simulations; and (3) synthesis and reflection. As a preliminary study, a model of intermittent irrigation was piloted in a learning environment involving 26 pre-service teacher students across three structured face-to-face sessions (each lasting 4 hours over two consecutive weeks), using project-based learning (PBL) combined with the jigsaw teaching technique. During these sessions, students collaboratively explored datasets on water surface height, drying intervals, drying duration, temperature variations, methane emissions, and rice yield through the CSDTs simulation tool "Rice Parameter" (https://csdt.org/projects/51384/run) as shown in Figure 1.

Through collaboration with the CSDTs team, simulations were developed to help students visualize how irrigation schedules influence ecological and agricultural outcomes. These simulations were co-created during the June workshops and refined using feedback from students and teachers. These hands-on, inquiry-based activities were designed to promote hypothesis generation, data interpretation, reflection, and application of findings, while reinforcing the values of community cooperation and sustainability inherent in Subak practices.



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ketika aku menerima initialize
point at angle 0
pergi ke x: -370 y: 0
atur ukuran ke 10 %
atur day counter ke 5
atur dry out day ke 80
atur water level ke 20
atur dry water level ke 3
atur rice growth ke 0
atur temperature ke 26
atur methane ke 10
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TANTANGAN I. Jalankan simulasi dengan mengklik bendera hijau. Amati tingkat permukaan air, suhu, pertumbuhan padi dan emisi metana pada layar. Bagaimana tinggi air dan suhu mempengaruhi produksi padi dan metana

TANTANGAN 2. Ubah tinggi air (di atas dan di bawah 5 cm). Bagaimana hubungan antara tinggi air, suhu, produksi padi dan emisi metana

TANTANGAN 3. Ubah fungsi suhu pada fungsi sinus menjadi lebih tinggi dan lebih rendah. Apa yang terjadi terhadap produksi padi dan emisi metana pada saat suhu meningkat dan menurun?

TANTANGAN 4. Atur tinggi permukaan air, suhu, lama pengeringan dan banyaknya pengeringan (day of counter), amati pertumbuhan padi dan emisi metana. Tentukan interaksi terbaik untuk semua faktor tersebut untuk menghasilkan pertanian yang optimal!...

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ketika 🏳 diklik
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ulangi 120 kali
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  atur efek color ke 0
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  stempel
  atur y ke 50
  atur efek color ke 26
  jika water level > 5
    atur rice growth ke rice growth + .5
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Figure 1. Computer model simulation used to explore the influence of irrigation schedules on ecological and agricultural outcomes.

2.4. Data Analysis Procedures

Data analysis focused on both qualitative narratives and quantitative measures from pre- and post-assessments, which were transformed into quantitative data. Open-ended answers were categorized into five main domains: (1) Understanding of the Subak System – Knowledge of Subak as a traditional, equitable water management system and its role in sustainable agriculture; (2) Greenhouse Gases and Methane Emissions – Awareness of how intermittent irrigation (irigasi berselang) influences methane emissions and environmental impact; (3) Impact of Water Level on Rice Growth – Understanding how optimal water levels affect rice yield and plant health; (4) Role of CSDTs Simulation – Recognition of how simulations help visualize and analyze water management and its environmental implications; (5) Relationship Between Temperature, Methane, and Yield – Insight into how temperature and water interact to influence methane production and crop productivity. Responses were scored using a rubric on a 0–2 scale (0 = no understanding, 2 = accurate and detailed understanding), with inter-rater reliability checks applied. Percentages of correct or in-depth responses were calculated for each topic and compared between pre- and post-tests to measure conceptual gains. This approach combines qualitative thematic coding with basic quantitative analysis to assess changes in student understanding.

3. RESULTS AND DISCUSSION

3.1. Results

The preliminary findings from the pre- and post-assessment indicate substantial improvements in students' comprehension of Subak-based sustainable agriculture and the application of CSDTs simulations. Quantitatively, there was an average conceptual gain of 27% across five key domains. These results demonstrate not only an increase in factual knowledge but also the development of higher-order reasoning, such as the ability to explain cause-effect relationships and connect theoretical knowledge with practical environmental solutions.

3.1.1. The Subak System

Prior to the intervention, 50% of participants viewed Subak merely as a general water management system, 30% understood some of its basic principles in the context of sustainable agriculture, while 20% lacked any deeper comprehension. Post-test results showed that 90% of participants demonstrated a comprehensive understanding of Subak as a culturally rooted system that promotes fairness, efficiency, and sustainability in water distribution, with the remaining 10% improving but retaining only a surface-level understanding while beginning to recognize its environmental significance.

A student's reflection before and after the intervention illustrates this conceptual shift: "Subak is an irrigation system used in Bali to channel water to rice fields. The water used comes from springs and flows into the rice fields. I don't know much about its impact on the environment, but I think Subak is used only for agricultural purposes." Meanwhile after learning activities she said "After participating in the simulation, I understand that Subak is not just an irrigation system but is closely related to environmental management. Subak helps maintain a fair distribution of water among farmers, which is important for agricultural sustainability. This system can also reduce water waste and help prevent drought, which has a positive impact on the surrounding ecosystem. I also learned that with this system, water management can be more efficient, reducing negative impacts on the environment.

The student's statements indicate a transition from a narrow, utilitarian perspective (seeing Subak only as a technical irrigation tool) to an interdisciplinary ecological understanding, where Subak is perceived as an integrated socio-environmental system. This transformation suggests that the simulation improved cognitive understanding by allowing students to link water management to broader ecological and cultural frameworks.

3.1.2. Greenhouse Gases and Methane Emissions.

Initially, 60% of participants had a general awareness of greenhouse gases but did not understand their specific link to rice agriculture, while 40% lacked this knowledge altogether. Post-assessment results showed that 85% of students could clearly explain how methane emissions are influenced by water management in rice paddies, as well as their cascading effects on soil temperature and crop yields. The remaining 15% demonstrated progress compared to their pre-test responses but still showed partial comprehension.

A student explained: "From the simulation, I learned that proper water management in rice fields greatly affects the methane emissions produced. When the rice fields are flooded for too long, the soil becomes deprived of oxygen, which encourages methane-producing microorganisms to multiply, increasing greenhouse gas emissions. This causes soil temperature to rise, which affects the growth of rice plants. However, if water management is carried out using the intermittent system, by adjusting the depth and frequency of water flooding, methane emissions can be significantly reduced. This not only reduces the impact of global warming but also increases yields because rice can grow in healthier conditions with sufficient water availability. Therefore, efficient water management helps create a balance between temperature, emissions, and optimal agricultural yields."

The response demonstrates an advanced conceptual grasp by moving beyond factual recall to describe a causal mechanism involving anaerobic conditions, microbial activity, and methane formation. The student's reasoning integrates sustainability principles, effectively linking scientific understanding with agricultural practice.

3.1.3. The Impact of Water Level on Rice Growth.

Before the learning session, 55% of students recognized that water is essential for rice growth but did not understand the optimal water level, while 45% were unaware of its critical role in maintaining crop yield. After the post-test, 90% demonstrated a clear understanding of the importance of water-level control for achieving optimal yield and reducing methane emissions, with 10% still showing partial confusion.

A student highlighted this insight: "Through the simulation I participated in, I realized how important proper water-level management in rice fields is to support optimal rice growth. If the water is too high and continuously floods the rice fields, the plant roots will lack oxygen, which disrupts rice growth and reduces yields. In addition, this anaerobic condition (without oxygen) encourages methane-producing microorganisms to develop, resulting in greenhouse gas emissions. Conversely, intermittent water management, where water is applied at certain intervals, reduces methane formation because the soil has time to re-oxygenate, while also supporting healthy rice growth. Therefore, proper water-level management not only helps achieve optimal yields but also reduces negative environmental impacts by suppressing methane emissions."

The response reflects a multidimensional understanding: the student is not only aware of the agronomic factors influencing rice growth but also recognizes the environmental trade-offs between water overuse and greenhouse gas emissions. This demonstrates that the CSDTs simulations effectively enhanced both scientific reasoning and ecological awareness by encouraging students to analyze practical environmental scenarios.

3.1.4. The Role of CSDTs Simulations in Water Management.

Prior to the intervention, 50% of participants did not understand how technology or simulations could be applied to optimize irrigation, while the remaining 50% were aware of the concept but lacked knowledge of practical applications. After the post-test, 95% of students reported an appreciation of how simulations support data-driven and efficient water management strategies, while 5% remained uncertain about real-world implementation.

As expressed by one student: "Previously, I thought high temperatures only affected rice yields, but after participating in the simulation, I realized that high temperatures are also directly related to increased methane emissions in rice fields. When the temperature rises, the soil becomes more active and stimulates methane-producing microorganisms, which in turn affects soil quality and rice yields. In addition, I also learned that proper water-level management can reduce methane emissions and maintain yields. I now understand that for optimal yields, we need to manage both temperature and water wisely, not just focus on one factor."

This statement shows that the simulation successfully prompted systems thinking by enabling the student to recognize interdependencies among multiple variables—water, temperature, soil conditions, and greenhouse gas emissions. Thus, the simulation served as an effective tool to bridge theoretical concepts with real-world agricultural challenges.

3.1.5. Relationship Between Temperature, Methane Emissions, and Rice Yield.

In the pre-test, 40% of students recognized that temperature and methane emissions impact crop yields but failed to grasp their complex interactions, while 60% had limited knowledge. After the post-test, 85% of students demonstrated the ability to explain how high temperatures combined with excessive water levels increase methane emissions, thereby lowering crop yields. Approximately 15% retained only partial understanding of these dynamics.

One student remarked: "After participating in the simulation, I truly understand how high temperatures not only directly affect rice growth but also cause increased methane emissions. It turns out that methane produced by flooded rice fields under high temperatures has a negative impact on the environment. I just learned that by managing water levels in rice fields, we can suppress methane emissions, maintain stable temperatures, and ultimately increase yields. Previously, I thought only water affected plants, but now I know that temperature and methane emissions are very closely related and influence each other."

This insight indicates a significant shift from a single-factor perspective to a systems-level understanding. The student now recognizes that agricultural outcomes are shaped by dynamic interactions among environmental variables, which is crucial for fostering critical thinking, systems thinking, and problem-solving in sustainable farming practices.

As summarized in Table 1, the understanding of Subak as a cultural and ecological irrigation system increased from 50% to 90% (an improvement of 40%). Similarly, comprehension of the relationship between greenhouse gas emissions and water management rose by 25%, while understanding of the impact of water levels on rice growth improved by 35%. Awareness of the role of CSDTs simulations as interactive learning tools showed the highest growth, with a 45% increase, and understanding of the link between temperature, methane emissions, and rice yield also increased by 45%. These results reinforce the quantitative evidence of conceptual gains across all domains.

Table 1. Pre- and Post-Assessment Results

Domain	Pre-Test (%)	Post-Test (%)	Improvement (%)
Understanding of Subak	50	90	40
Greenhouse Gas & Methane Emission	60	85	25
Impact of Water Level on Rice Growth	55	90	35
Role of CSDTs Simulation	50	95	45
Link between Temperature, Methane, Yield	40	85	45

3.1.6. Qualitative Insights into Conceptual Gains.

The qualitative responses provide deeper insights into the quantitative improvements presented in Table 1, illustrating how students' conceptual understanding evolved through the learning interventions. Prior to the simulation, participants often described Subak in simplistic or fragmented terms, such as "a system of irrigation for rice paddies in Bali," indicating a lack of awareness of its cultural and ecological dimensions. Following the CSDTs-based learning sessions, the same participant reflected, "Subak is not just irrigation but a holistic system that ensures water fairness, maintains environmental sustainability, and improves crop productivity." This transformation highlights how the integration of interactive simulations and context-based instruction can broaden students' perspectives, linking technical irrigation knowledge with socio-environmental values.

Example 1 (Water Level Impact) further reinforces this finding. Before the simulation, many students provided general or incomplete responses, such as, "Water is important for rice growth, but I am not sure how its level affects the plants." In contrast, after the intervention, a participant remarked, "I realized that too much water reduces oxygen in the soil, which harms the roots and lowers yield. The simulation showed that maintaining a medium water level ensures optimal growth and reduces methane emissions." This statement demonstrates how students transitioned from passive recall of facts to active reasoning based on empirical observation, connecting water management strategies to both agricultural productivity and environmental impacts.

Similarly, Example 2 (Temperature-Methane-Yield Relationship) shows a progression toward systems thinking. Initially, students lacked understanding of how temperature interacts with methane emissions and crop yields. One participant reflected, "Previously, I thought temperature only affects plant growth. Now, I understand that higher temperatures increase methane emissions in flooded paddies. Using intermittent irrigation combined with optimal temperature can improve yields and minimize greenhouse gases." This evolving comprehension underscores the value of simulations in enabling students to analyze dynamic interactions between environmental variables. Collectively, these qualitative insights complement the quantitative gains, affirming that the CSDTs simulations not only enhanced factual knowledge but also fostered integrative and critical thinking about sustainable agricultural practices.

3.2. Discussion

The findings from the pre- and post-assessments, which revealed an average 27% improvement across five conceptual domains, indicate that the Subak-based generative STEM model may lead to substantial enhancement in students' ecological literacy, systems thinking, and cultural awareness. This improvement is demonstrated not only by the quantitative results (e.g., understanding of Subak increasing from 50% to 90%) but also by qualitative responses showing how participants shifted from viewing Subak as a mere technical irrigation tool to recognizing it as a holistic socio-ecological system. Such a cognitive transition is evidenced by direct student reflections (see Section 3.1), where participants highlighted the intertwined roles of water distribution, environmental balance, and sustainability in Subak practices.

Compared with previous studies that focused primarily on conceptualizing culturally responsive STEM education without extensive empirical validation (Tapia et al., 2017; Gay, 2013; Simpson et al., 2023), this research advances the field by combining computational simulations (CSDTs) with real-world agroecological data derived from Subak irrigation practices. The integration of entropic modulation—a principle often discussed theoretically in ecological and computational contexts (Eglash et al., 2023 ; 2024b)—into a classroom-based framework represents a novel pedagogical approach. This approach demonstrates a forward step by not only embedding Indigenous ecological knowledge but also operationalizing it through interactive, data-driven simulations, thereby bridging the gap between theory and application.

The novelty of this study also lies in its explicit focus on measurable indicators, as shown by the pre/post assessment data (see Table 1), and its emphasis on students' higher-order reasoning. Participant quotes (Sections 3.2–3.5) illustrate how learners began linking methane emissions, water-level regulation, and crop yield with climate-related challenges—a depth of understanding that is often missing from conventional STEM curricula. This aligns with, yet extends, the work of Brown et al. (2018) and McCollough et al. (2019), by demonstrating that culturally grounded models can yield both cognitive and affective learning outcomes.

Despite these promising results, certain limitations should be acknowledged. The study involved a relatively small sample (26 pre-service teachers), which may limit the generalizability of the findings. Additionally, while students exhibited conceptual gains, about 10–15% still showed partial understanding of complex relationships (e.g., temperature-methane-yield interactions), suggesting the need for extended learning cycles and more robust scaffolding. There were also practical barriers such as limited digital infrastructure in rural school contexts and varying teacher readiness, which may challenge the scalability of the model.

For future research, we recommend three main directions: (1) expanding the scope of participants to include in-service teachers and secondary students across diverse ecological settings, (2) developing standardized rubrics to measure constructs like agency, ecological literacy, and systems thinking, and (3) exploring longitudinal impacts by assessing how knowledge and practices evolve beyond the immediate intervention. Furthermore, the integration of emerging technologies, such as IoT-based environmental sensors and predictive modeling, could enhance the authenticity and interactivity of the simulations, further bridging the gap between modern STEM tools and traditional ecological systems.

In summary, this study contributes a significant step forward by demonstrating that a generative STEM model, grounded in Subak's cultural and ecological logic, has the potential to both decolonize and modernize science education. It complements previous literature while offering a scalable, data-driven, and culturally embedded approach that directly connects STEM learning with sustainability and community values.

4. CONCLUSION

The findings indicate that integrating Indigenous ecological knowledge, particularly the Subak system, has enhanced students' engagement and understanding, as shown by a 27% improvement in conceptual comprehension. Despite initial confusion about the effect of water height on rice growth, the overall results highlight the model's potential for decolonizing STEM education.

This study advances a generative STEM model that draws on the ecological wisdom of Bali's Subak system. By integrating Indigenous knowledge with modern science learning, the model reframes STEM as culturally grounded and systems-oriented. Empirical data (Sections 3.1–3.5) show improved student engagement, interest in environmental monitoring, and stronger connections between scientific concepts and local practices. Beyond tools like simulations and sensors, the approach positions learners as co-creators of knowledge, fostering deeper engagement and ecological awareness.

The model bridges knowledge systems, challenging dichotomies between traditional and scientific perspectives. By placing Indigenous frameworks at the core of educational design, it fosters ecological awareness, cultural identity, and critical thinking. Unlike conventional STEM approaches, this model integrates cultural narratives and ecological data, offering a holistic pathway that emphasizes systems thinking, sustainability, and local relevance.

Ultimately, this research contributes to the movement of decolonizing science education, offering curricular innovation and an epistemological shift that values reciprocity, complexity, and collective stewardship. The study acknowledges limitations such as the pilot's small scale and potential challenges in embedding local knowledge into standardized curricula. Theoretically, this research enriches generative STEM discourse by linking entropic modulation and Indigenous ecological knowledge. Practically, it provides a scalable framework and simulation-based tools to foster ecological literacy and culturally relevant learning. As global challenges intensify, education systems must evolve to cultivate learners who are both scientifically literate and ecologically attuned.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge the anticipated involvement of Subak communities in Bali, whose ecological wisdom and cultural practices are central to this proposed study. Appreciation is also extended to educational collaborators for their initial engagement and encouragement. This research plan is supported by the 2025 Fundamental Research Grant from the Ministry of High Education, Research, and Technology (Kemdiksaintek), Government of the Republic of Indonesia, 129/C3/DT.05.00/PL/2025. The article was composed with the aid of artificial intelligence tools—ChatGPT (OpenAI), DeepSeek, and Scite AI—which contributed to literature mapping, conceptual articulation, and textual refinement. Responsibility for all content and interpretations remains with the authors.

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