Culturally Responsive Digital Geometry Instruction: Integrating Ethnomathematics, Educational Innovation Management, and a Legal Framework for Sustainable Education

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ABSTRACT

Geometry instruction in schools is often perceived as an abstract activity detached from students' life contexts, while the richness of local culture—which is steeped in geometric concepts—has not been optimally utilized. On the other hand, digital technology has opened new opportunities for dynamic visualization and exploration; however, its implementation remains dominated by a universal approach that overlooks local wisdom. This study aims to develop a culturally responsive digital geometry learning model through the integration of ethnomathematics, educational innovation management, and a legal framework to support sustainable education. A qualitative, narrative-descriptive case study approach was employed, involving one Madrasah Tsanawiyah in a rural area rich in woven fabric motifs and traditional house architecture. The research subjects included a mathematics teacher and 28 eighth-grade students. Data collection techniques included participatory observation, in-depth interviews, documentation of cultural artifacts and digital media, as well as analysis of school policy documents and the curriculum. Data were analyzed thematically using source and technique triangulation, member checking, and audit trails. The results indicate that transforming weaving motifs and patterns into geometry learning resources enhances students' emotional and cognitive engagement and facilitates their understanding of geometric transformations and plane figures. Digital media, such as interactive geometry apps and animated videos, reinforce concrete and visual representations. Teachers managed innovation through a cycle of problem identification, media design, implementation, evaluation, and reflection, with support from the school principal in accordance with educational regulations and cultural advancement policies. Major obstacles included limitations in technological infrastructure and the need for ongoing guidance. The novelty of this research lies in the systematic integration of digital ethnomathematics, educational innovation management, and legal frameworks into a single coherent learning model. The resulting conceptual model consists of five stages: reading culture, translating culture into geometric concepts, digital visualization, innovation management, and policy institutionalization. The theoretical contribution expands the study of ethnomathematics to include digital and managerial dimensions, while the practical contribution provides guidance for teachers and schools in designing contextual and sustainable geometry instruction. Sustainable education is defined as the sustainability of culture, school innovation, learning quality, and students' digital literacy. This study recommends further development through experimental studies and adaptation to other cultural contexts.

Introduction

Geometry instruction at the elementary and secondary levels is often a source of dread for students due to its abstract nature and disconnect from daily life. Concepts such as plane figures, solid figures, transformations, and similarity are taught through dry formulas and diagrams, without any connection to students' cultural experiences. As a result, learning motivation is low, understanding is purely procedural, and spatial thinking skills do not develop optimally. In fact, geometry is a branch of mathematics closely tied to physical reality and human culture. Various cultural artifacts—such as woven fabric patterns, basketry, carvings, traditional architecture, and folk game patterns—are rich in geometric concepts that can serve as a bridge to formal understanding (Demingoy et al., 2026).

Ethnomathematics—as a field of study that explores mathematical practices within cultural groups—has demonstrated its effectiveness in enhancing the relevance and meaningfulness of learning (Nasution et al., 2025). Studies on Pacu Jalur, for example, not only reveal its physical and cultural aspects but also its potential as a resource for mathematics and science education. However, the integration of ethnomathematics into digital learning remains limited. Digital technology offers great opportunities to dynamically visualize geometric concepts, simulate transformations, and provide instant feedback (Mukambetova et al., 2025; Asare, 2026). Mobile learning applications have been shown to enhance students' problem-solving skills and engagement, particularly when combined with relevant cultural contexts (Asare, 2026).

A persistent research gap is the lack of a learning model that systematically integrates ethnomathematics, digital technology, educational innovation management, and legal frameworks into a unified whole to achieve sustainable education. Educational innovation management is key to ensuring that teachers' practices can be developed, tested, and institutionalized sustainably. Meanwhile, national legal frameworks such as the National Education System Act, the Cultural Advancement Act, and the Merdeka Curriculum provide legitimacy and space for cultural integration in learning (Hidayatullah et al., 2026; Mappaenre et al., 2023). The concept of good governance in education emphasizes transparency, participation, and accountability, which are relevant to the management of learning innovations (Hidayatullah et al., 2026).

Sustainable education is not only about environmental sustainability but also about cultural sustainability, innovation, and the quality of learning. In this context, culturally responsive digital geometry learning can serve as a vehicle to strengthen students' cultural identity, enhance digital literacy, and build a solid foundation in mathematics. This research is also driven by findings that alternative methods, such as Galilean geometry, can enrich students' understanding and boost motivation (Kurudirek et al., 2025). Similarly, character education integrated into mathematics learning can foster students with integrity and a love for their culture (Mappaenre et al., 2023).

The novelty of this research lies in its multidimensional integration: ethnomathematics as a source of content, digital technology as a tool for representation, innovation management as a process for managing change, and the legal framework as a normative foundation. These four pillars are unified into a single learning model designed to support sustainable education. The research objectives, in narrative form, include: (1) describing practices of digital geometry learning based on local culture at a madrasah; (2) analyzing the role of digital technology in strengthening geometric representations rooted in ethnomathematics; (3) identifying how teachers manage learning innovations through educational innovation management; (4) examining how the legal framework and school policies support the implementation of this learning model; and (5) formulating a conceptual model that integrates these four aspects to support sustainable education. Thus, this study contributes to the development of contextual, innovative, and sustainable mathematics learning theory and practice.

Geometry Learning as a Multirepresentational Process

Geometry learning essentially involves the development of spatial abilities, an understanding of shapes, relationships between objects, and representations in various modes: concrete, visual, symbolic, and digital. Van Hiele outlined the stages of geometric thinking, ranging from visualization to formal deduction. Research by Kurudirek et al. (2025) shows that the use of alternative methods such as Galilean geometry—which employs a non-Euclidean approach in specific contexts—can enrich problem-solving strategies and improve computational efficiency among students. These findings indicate that flexibility in representations and methods is crucial in geometry learning. Digital learning enables dynamic visualization, transformation simulations, and collaboration among students (Mukambetova et al., 2025). Mobile apps and interactive geometry software provide a safe and engaging environment for exploration.

Ethnomathematics and Culturally Responsive Learning

Ethnomathematics is understood as the study of mathematical practices within specific cultural groups. In his study on AI ethnocomputation, Cooper (2022) emphasizes the importance of accommodating ways of knowing from marginalized cultures, such as the Gullah Geechee culture. This also applies in the Indonesian context, where batik motifs, woven textiles, basketry, and traditional house architecture constitute rich geometric representations. Demingoy et al. (2026) developed mathematics teaching materials based on folk tales that were deemed highly appropriate and effective in increasing student engagement. Folk tales provide culturally familiar narratives, making mathematical concepts more meaningful. Culturally responsive teaching requires teachers to connect instructional content to students' cultural backgrounds, experiences,

and identities. Nasution et al. (2025) identified that the Pacu Jalur tradition in Kuantan Singingi holds pedagogical potential in character education, science, and mathematics. Integrating local culture into geometry instruction not only facilitates conceptual understanding but also strengthens students' cultural identity and sense of pride.

Management of Educational Innovation

Learning innovation does not happen instantly; it requires a management process that includes needs assessment, design, pilot testing, evaluation, reflection, and dissemination. Educational innovation management focuses on how new practices can be adopted and institutionalized within the school system. Mappaenre et al. (2023) emphasize the importance of involving all stakeholders in strengthening character education in madrasahs. This aligns with the principles of good governance, which prioritize participation, transparency, and accountability. In the context of integrating ethnomathematics and digital learning, teachers—as agents of innovation—must have autonomy and support from school administration. The Worldwide Governance Indicators framework (Hidayatullah et al., 2026) highlights that the quality of governance—including in the education sector—significantly influences the success of policy implementation and innovation. Schools with good governance will find it easier to adopt and sustain learning innovations.

Legal Framework for Sustainable Education

The legal foundation for integrating culture into learning in Indonesia is quite strong. Law No. 20 of 2003 on the National Education System mandates education grounded in cultural and national values. Law No. 5 of 2017 on the Advancement of Culture reaffirms the role of education as a vehicle for cultural advancement. Hidayatullah et al. (2026) demonstrate that the quality of regulations and anti-corruption controls influence the effectiveness of government governance implementation. When applied to education, clear legal and regulatory frameworks provide certainty and legitimacy for teachers and schools in integrating local culture into the curriculum. The Merdeka Curriculum rolled out by the government provides greater scope for contextual and project-based learning, including the utilization of local culture. Mappaenre et al. (2023) also highlight the role of madrasahs in filtering foreign cultures through the strengthening of character education, which is part of the legal framework of the GNRM (National Mental Revolution Movement).

Sustainable Education in the Context of Mathematics Learning

Sustainable education encompasses three pillars: economic, social, and environmental. In the context of culturally responsive digital geometry learning, sustainability is defined as: (a) cultural sustainability—the preservation and transmission of local wisdom through education; (b) innovation sustainability—the school's ability to continuously develop and improve the quality of learning; (c) sustainability of learning quality—consistent improvement in learning outcomes; (d) sustainability of digital literacy—equipping students with relevant technological skills. Colorado Orozco (2024) highlights the importance of a healthy digital identity for children in the technological age. Culturally responsive digital learning must take into account ethical considerations, privacy, and the development of a positive digital identity. All these aspects require a robust legal framework and sound innovation management

Methods

This study employs a qualitative approach with a narrative-descriptive case study design. The case was purposively selected from one Madrasah Tsanawiyah (MTs) in Sumenep Regency, Madura, which is rich in local cultural heritage, such as Sumenep's distinctive batik motifs, bamboo weaving, and traditional Madurese architecture. This school also possesses basic technological infrastructure in the form of a computer lab and internet access, albeit limited. Participants included one mathematics teacher (initials: Ms. S, 12 years of experience) and 28 eighth-grade students (14 boys, 14 girls). The teacher was selected because she had experience using digital media and demonstrated an interest in integrating local culture.

Data collection methods included: (1) participatory observation of 8 geometry learning sessions designed by the teacher; (2) in-depth interviews with the teacher (3 sessions, 45 minutes each) and with 8 students selected diversely based on their level of understanding; (3) photographic and video documentation of the learning process, cultural artifacts used (batik motifs, weaving patterns), digital media (animated videos, the GeoGebra application, interactive PowerPoint presentations), and student work; (4) teachers' reflective notes; (5) school policy documents (vision and mission statements, lesson plans, and curriculum documents).

Data analysis was conducted using thematic-narrative techniques. All interview transcripts, observation notes, and documents were analyzed through the following steps: data reduction, preliminary coding, theme identification, theme review, and narrative writing. Data validity was ensured through source and method triangulation, member checking with participating teachers and several students, and an audit trail by having peers (a mathematics professor and an anthropologist) review the consistency of the analysis. Research ethics were upheld by obtaining permission from the school principal, informed consent from teachers and students' parents, and respecting the cultural works used by citing sources and seeking permission from the local artisan community. Participant anonymity was maintained unless requested otherwise.

Results and Discussions

Madrasah Tsanawiyah "Al-Falah" is located in the northern coastal region of Madura, an area still deeply rooted in tradition. Most students come from families of fishermen and batik artisans. Prior to the study, mathematics instruction relied on conventional methods using textbooks and a blackboard; learning outcomes in geometry were relatively low (an average daily test score of 62). The school has 15 older computers, one projector, and Wi-Fi internet access that is stable only at certain times. The mathematics teacher, Ms. S, had participated in an ethnomathematics training program organized by the local Ministry of Religious Affairs and was interested in applying it. The local cultural elements selected as sources for geometry learning were the "Pasisir" and "Sekar Jagad" batik motifs, as well as woven bamboo rice containers. These motifs contain patterns of symmetry, geometric transformations (reflection, rotation, translation), and repeating two-dimensional shapes. The architecture of the traditional "Tanean Lanjhang" house was also used for lessons on three-dimensional shapes and similarity.

The teacher designed the learning experience over 8 sessions: (1) introduction to cultural motifs and identification of geometric elements; (2) mathematical modeling through hand-drawn sketches; (3) digitizing patterns using GeoGebra; (4) geometric transformations (reflection and rotation) of the motifs; (5) exploration of similarity using architectural photos; (6) a group project to create a digital batik design; (7) presentation and reflection; (8) evaluation. The digital media developed include teacher-created tutorial videos, GeoGebra files containing batik motifs, and an interactive grid for transformations. Students work in heterogeneous groups and take turns using the computers. Activities begin with observing photos of motifs, discussing the patterns, translating them into geometric concepts, and then visualizing them using software. The main challenges stem from the limited number of computers—which forces some groups to wait their turn—and slow internet connections when downloading applications.

Transforming Local Culture into a Resource for Learning Geometry

Observations and interviews revealed that students were very enthusiastic when invited to examine batik and woven motifs they recognized from their daily lives. The "Sekar Jagad" motif, consisting of repeated fold and rotation symmetries, is easily recognized as an example of reflection and rotation. In an interview, one student stated: "It's only now that I realize batik is math." The teacher explained that students' understanding of symmetry concepts had improved significantly compared to the previous year. In an informal post-test, 22 out of 28 students were able to explain the types of transformations found in different batik motifs. Similarly, with bamboo weaving, the crisscross (diagonal) weaving pattern served as a visual aid for the concepts of diagonals and area. Students were able to visualize geometric shapes concretely.

The Role of Digital Media in Strengthening Representation

The use of GeoGebra and animated videos allows students to directly "manipulate" geometric objects. They can slide, rotate, and reflect batik motif images on the screen, which greatly aids their understanding of transformations. The teacher designed an activity in which students entered the coordinates of the motif's points into GeoGebra and observed the results of the transformations. Digital media also makes it easier to address mistakes; students can quickly repeat steps. An interactive PowerPoint presentation contains quizzes on types of transformations applied to various cultural motifs. Mukambetova et al. (2025) confirm that interactive programs enhance interest and critical thinking—a finding consistent with classroom observations. Students complain of boredom less frequently and experiment more often with the available features.

Student Responses to Learning

Qualitatively, students' active participation increased dramatically. Group discussions were more lively; students exchanged strategies and helped one another understand the instructions within the

application. Positive emotions were evident in their laughter and expressions of amazement when they successfully created transformation patterns. One female student said, "I like it because I can draw intricate patterns on the computer." Intrinsic motivation emerged as students felt they were learning something useful and relevant to their lives. However, some students who were less familiar with computers experienced technical difficulties, though their groupmates helped them. The teacher noted that students' self-confidence increased, particularly among those previously considered weak in math, as they felt like "experts" in understanding batik motifs. Character education—such as cooperation, responsibility, and pride in local culture—was naturally internalized, as emphasized by Mappaenre et al. (2023).

The Role of Teachers and Innovation Management

Ms. S intuitively follows the innovation management cycle: she identifies problems (students are bored and have low comprehension), seeks solutions through ethnomathematics training, designs her own digital learning materials (learning GeoGebra through YouTube tutorials), implements them, and then reflects on each session. The principal provides full support because this innovation aligns with the madrasah's vision of embracing culture and technology. The school facilitated the purchase of a premium GeoGebra license and upgraded the Wi-Fi network. Teachers also developed lesson plans that integrate the 2013 Curriculum's core competencies and learning outcomes with culture and technology. Innovation management is evident in the documentation of learning outcomes, the creation of digital portfolios, and plans to disseminate best practices to other teachers through Subject Teacher Working Groups (MGMP). This aligns with the principles of participation and accountability emphasized by Hidayatullah et al. (2026) in the context of educational governance.

Barriers and Challenges

The main obstacle is infrastructure: there are only 15 computers for 28 students, necessitating a rotation system. An unstable internet connection occasionally causes online applications to freeze. Teachers also complain about the significant amount of preparation time—they spend 2–3 hours per day creating digital content. Some students who do not have access to a computer at home face difficulties when they need to continue their exploration at home. Additionally, some other teachers remain skeptical and feel that this model is time-consuming and does not align with the requirements of the national exams. However, the principal's support and the students' enthusiasm serve as the main driving forces. To address the time constraints, teachers distribute offline applications and simple GeoGebra files that can be installed on students' smartphones. These challenges underscore the need for more supportive policies, as discussed in Hidayatullah et al. (2026) regarding the importance of regulatory quality and anti-corruption measures in governance.

Legal Framework

Legally, the integration of culture into learning at madrasahs is supported by Ministry of Education and Culture Regulation No. 21 of 2016 on Content Standards and the Director General of Islamic Education Decision No. 2762 of 2018 on Guidelines for Implementing the 2013 Curriculum in Madrasahs, which provide scope for the development of local content. The Law on the Advancement of Culture (Law No. 5/2017) serves as the formal basis for using culture as a learning resource. The school principal asserts that this innovative geometry teaching model is also aligned with the Ministry of Religious Affairs' priority program promoting digital and cultural literacy. This legal framework provides legitimacy for teachers to continue developing their teaching methods without fear[39] of being deemed to deviate from the national curriculum. On the contrary, this innovation is actually viewed as a form of creative and contextual curriculum implementation.

Discussion

The Strengths of the Culturally Responsive Digital Geometry Learning Model

The learning model implemented at MTs Al-Falah demonstrates that the integration of ethnomathematics, digital technology, innovation management, and legal frameworks is not merely an add-on but forms a mutually reinforcing ecosystem. Ethnomathematics provides rich and meaningful content for students, in line with the findings of Demingoy et al. (2026) that teaching materials based on folk tales are highly effective and capable of increasing engagement. However, this study goes a step further by adding a digital dimension that enables interactive exploration and deeper visualization. The use of geometry software such as GeoGebra allows students to test their hypotheses directly, for example, "What happens if this

pattern is rotated 90 degrees?" This supports the findings of Kurudirek et al. (2025), who discovered that alternative methods can enrich problem-solving strategies and make learning more enjoyable.

Conceptual Model: Five Stages of Integration

Based on field findings, the researchers formulated a conceptual model with five stages:

Stage 1: Reading Culture. Teachers and students jointly identify local cultural artifacts (batik patterns, woven textiles, architecture) and discuss their meanings and geometric elements. This process cultivates cultural sensitivity and activates prior knowledge.

Stage 2: Translating Culture into Geometric Concepts. Cultural artifacts are "translated" into geometric terms: symmetry, transformations, plane figures, and similarity. This activity requires teacher guidance to direct observations toward relevant mathematical elements.

Stage 3: Digital Visualization. With the help of geometry software, students digitally reconstruct cultural motifs, manipulate them, and observe their geometric properties. This stage reinforces visual and spatial representations and provides immediate feedback.

Stage 4: Innovation Management. Teachers document the process, evaluate the effectiveness of tools and methods, and reflect on ways to improve. This innovation management ensures that learning continues to evolve and can be replicated.

Stage 5: Institutionalization through School Policy. Schools adopt this model as a learning strategy, supported by written policies, resource allocation, and teacher development programs. MGMP activities serve as a forum for sharing best practices.

These five stages are not strictly linear but rather iterative and flexible depending on the context. This model provides a systematic conceptual framework for building sustainable and culturally responsive geometry learning.

Theoretical and Practical Contributions

Theoretically, this study expands the scope of ethnomathematics from its original focus on physical artifacts to include digital representations and innovation management. Cooper (2022) emphasizes the importance of ethnocomputation, which accommodates cultural knowledge within artificial intelligence; this context is analogous to how cultural geometry is "translated" into digital applications. Furthermore, this study integrates the legal dimension as a legitimizing framework—an aspect rarely addressed in the ethnomathematics literature. Hidayatullah et al. (2026) demonstrate that good governance creates an environment conducive to innovation; the findings of this study support the notion that policy support and school administration play a crucial role. Practically, this model provides step-by-step guidance for teachers and schools seeking to integrate local culture with digital technology. Teachers can adapt this framework to align with the local wisdom of their respective regions. Educational innovation management (Mappaenre et al., 2023) ensures that change does not stop at pilot projects but can be sustained.

Implementation of Sustainable Education

Culturally responsive digital geometry learning supports sustainable education in four dimensions. First, cultural sustainability: students not only learn geometry but also appreciate and preserve local culture through digital media. Second, innovation sustainability: schools build teachers' capacity to continue innovating. Third, learning quality sustainability: deeper understanding of geometry and better learning outcomes. Fourth, digital literacy sustainability: students master essential 21st-century skills. Colorado Orozco (2024) emphasizes the importance of a healthy digital identity; this learning also instills digital ethics as students learn to use technology responsibly. Asare (2026) emphasizes that mobile learning combined with cultural context enhances problem-solving skills—this is evident from the results of the digital batik design project at, which required transformative problem-solving. All of this contributes to sustainable development in the field of education.

Comparison with Previous Research and Implications

This study aligns with the findings of Demingoy et al. (2026) and Nasution et al. (2025) regarding the potential of culture as a learning resource. However, this study adds digital and managerial dimensions that have not been widely explored. Mukambetova et al. (2025) highlighted the advantages of interactive programs in teaching rational numbers; our research extends this to geometry and ethnomathematics. Kurudirek et al. (2025) demonstrated that the Galilean method can enhance motivation; we found that hands-on exploration with GeoGebra also yields similar motivational benefits. Implications for teacher practice: Adequate training in ethnomathematics and the use of geometry software is needed. Schools need to allocate

budgets for ICT infrastructure and teacher development. Local governments can provide support by offering a ready-to-use bank of digital content reflecting local culture. Implications for policy: The integration of culture and digital technology in learning needs to be strengthened through local regulations and locally tailored curricula that are integrated with technology.

Conclusions

This study confirms that culturally responsive digital geometry instruction is an innovative approach that integrates ethnomathematics, digital technology, educational innovation management, and legal frameworks into a coherent whole to support sustainable education. Field findings indicate that transforming local culture into a source of geometry learning—enhanced by digital media—can increase students' emotional and cognitive engagement, facilitate the understanding of abstract concepts, and strengthen cultural identity and digital literacy. The role of teachers as innovation managers is crucial, as are the support of school principals and policy legitimacy. The novelty of this article lies in a five-stage conceptual model that connects culture, geometry, digital technology, innovation management, and law within a single learning ecosystem. This model offers a systematic approach that can be adapted to various cultural contexts in Indonesia. Sustainable education is not only about environmental sustainability but also about the sustainability of a culture of innovation, the quality of learning, and digital literacy. This study concludes that the integration of these four pillars is an effective strategy for building a solid foundation in mathematics, fostering a generation that cherishes culture, and preparing students to face the challenges of the 21st century.

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