

CULTURO-TECHNO- CONTEXTUAL-AI FOR STEAM EDUCATION SUSTAINABILITY

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Abstract

The integration of Artificial Intelligence (AI) into education has transformed global STEAM discourse, yet African and Global South systems face persistent challenges including inequitable access, cultural irrelevance, technological dependency, weak contextualization, and fragmented practices. Conventional AI-driven models often privilege Western-oriented, technologically deterministic approaches that marginalize indigenous knowledge systems and learners' socio-cultural realities, thereby undermining meaningful learning, engagement, and sustainability. This theoretical paper conceptualizes the Culturo-Techno-Contextual Artificial Intelligence (CTCAI) Pedagogy as a transformative framework for equitable, culturally responsive, and sustainable STEAM education. Anchored on Constructivism, Social Constructivism, TPACK, CHAT, Connectivism, and Connectionism. CTCAI extends Professor Peter Okebukola's Culturo-Techno-Contextual Approach (CTCA) by embedding AI within local languages, cultural practices, environmental conditions, and community-centred problem-solving. It

positions AI as a culturally adaptive pedagogical partner that supports contextual intelligence, personalized learning, learner agency, ethical reasoning, creativity, and sustainability-oriented innovation, enabling students to become active co-creators who interrogate and culturally align AI outputs. The CTCAI STEAM Sustainability Model integrates indigenous knowledge, AI-supported learning, contextual problem-solving, and interdisciplinary collaboration to foster twenty-first-century competencies such as systems thinking, innovation, resilience, and transformative agency. Empirical evidence from CTCA studies shows significant gains in achievement, engagement, conceptual understanding, and emotional well-being. While acknowledging challenges like digital inequality, infrastructure gaps, algorithmic bias, and teacher preparedness, the paper recommends culturally responsive AI audits, localized datasets, multilingual systems, and community-driven reforms. Ultimately, CTCAI represents a paradigm shift toward decolonizing AI education, promoting technological sovereignty, and advancing SDG 4 through human-centred, culturally aligned, and sustainable development.

Keywords: STEAM education, Culturo-Techno Contextual-AI, Sustainability

Introduction

Education is undergoing significant changes worldwide. SDG 4 calls for inclusive and quality education that supports learning throughout life. Within this broader agenda, STEAM education provides opportunities for learners to develop creativity, collaboration, critical thinking, and problem-solving skills. However, unequal access to educational opportunities and differences in learning outcomes persist, particularly in settings where educational reforms pay insufficient attention to learners' cultural backgrounds and

everyday realities. Such gaps can weaken the sustainability and relevance of educational practices (Abimbola et al., 2024; Baylon et al., 2025; Sabiteka et al., 2025). These concerns point to the importance of pedagogies that are responsive to learners' cultures and contexts. Artificial intelligence (AI) offers new possibilities for improving STEAM education, particularly through adaptive learning, learner engagement, and personalised support. Yet its effective use remains difficult in many African settings because of inadequate infrastructure, weak policy support, unreliable internet connectivity, and limited teacher preparation (Adesina et al., 2025; Olagunju et al., 2025; Raimi et al., 2024). At the same time, teacher-centred and examination-oriented practices often leave little room for inquiry, creativity, and learning that addresses sustainability issues. The Culturo-Techno-Contextual-AI (CTCAI) framework seeks to respond to these concerns by bringing together culture, technology, contextualisation, and AI in ways that make STEAM learning more inclusive and relevant to local realities (Elmahdi et al., 2025; Jufrida et al., 2025; Okada et al., 2025; Sharma, 2025). CTCAI encourages learners to use scientific and technological knowledge to engage with problems within their communities. At the same time, it supports equitable access, adaptive teaching, and personalised feedback. By linking science, technology, creativity, and local concerns, the approach creates opportunities to address issues such as climate change, renewable energy, environmental sustainability, and public health. Collaborative and project-based activities can also help learners build communication, teamwork, systems thinking, digital literacy, and ethical awareness. In this way, the framework offers possibilities for adapting teaching to under-resourced environments while supporting learning outcomes, workforce readiness, lifelong learning, and progress towards SDG 4 (Eguchi et al., 2021; Nguyen, 2025; Samuel et al., 2023; Viberg et al., 2024; Xia et al., 2024).

STEAM Education

STEAM education brings Science, Technology, Engineering, Arts, and Mathematics together through interdisciplinary learning. Its emphasis is on inquiry, creativity, collaboration, critical thinking, and solving problems that have relevance beyond the classroom (Adesina, 2025; Nguyen, 2025). The approach developed from STEM and was further formalised by Georgette Yakman through the inclusion of the Arts and humanities. This addition gives greater attention to creativity, ethics, design, and human-centred thinking when learners engage with sustainability, innovation, and social problems (Dignam et al., 2024; Gavrilas & Kotsis, 2025; Li, 2023; Mei et al., 2023). The foundations of STEAM can be linked to socio-constructivism, integrated curriculum theory, interdisciplinarity, and twenty-first-century skills frameworks. These perspectives support active and collaborative learning in which learners connect what they study with their own experiences. In contrast to a narrow STEM focus, STEAM gives greater room to creativity, democratic participation, inclusivity, and holistic development alongside technical knowledge (Adesina, 2025; Li, 2023; Mei et al., 2023). Studies have associated STEAM learning with improvements in learner engagement, motivation, higher-order thinking, creativity, problem-solving, innovation readiness, and participation among learners from different backgrounds.

The value of STEAM can be seen across educational levels, from early childhood through higher education. When learners engage in authentic STEAM activities, they are more likely to develop curiosity, confidence, collaboration, participation, and an understanding of sustainability issues (Adesina, 2022; Habib, 2025; Ng et al., 2022; Su et al., 2024; Wahyuningsih et al., 2020). Nevertheless, implementation is not without difficulties. Common concerns include superficial integration of the Arts, inadequate teacher preparation, limited resources, rigid curricula, and assessment systems that do not encourage

interdisciplinary learning. In some cases, the Arts are still treated as less important than the STEM components, which can reduce disciplinary depth and weaken the intended benefits of STEAM. Effective implementation therefore depends on genuine interdisciplinarity, sustained professional development, flexible curricula, supportive policies, sufficient resources, and appropriate assessment practices (Dignam et al., 2024; Mei et al., 2023). Future work should also pay greater attention to inclusion, digital integration, sustainability, and long-term research so that learners can become creative, ethical, adaptable, and responsible citizens capable of responding to complex social challenges.

Sustainability in STEAM education has developed from the meeting point between Education for Sustainable Development and the STEAM movement, with UNESCO's SDG priorities, particularly SDG 4.7, providing an important policy foundation (Gavari-Starkie et al., 2022; Rafiq-uz-Zaman, 2025; Saad et al., 2026; Sylla et al., 2025). By bringing the Arts and humanities into STEM, STEAM creates room for creativity, ethical reasoning, and human-centred thinking. Sustainability therefore becomes part of meaningful learning rather than simply another topic added to the curriculum (Rafiq-uz-Zaman, 2025; Saad et al., 2026). Sustainability-oriented STEAM learning draws on scientific, technological, engineering, artistic, and mathematical knowledge to help learners understand complex systems, consider the consequences of human actions, and make socially and environmentally responsible decisions. Meaningful STEAM experiences consequently connect curriculum, teaching approaches, and assessment with real-world socio-ecological concerns. The need for such an approach is evident in challenges such as climate change, renewable energy, inequality, and environmental degradation. These problems cannot easily be addressed from a single disciplinary perspective; they require collaboration, creativity,

and ethical engagement (Gavari-Starkie et al., 2022; Saad et al., 2026). The Arts contribute to this process by encouraging imagination, emotional engagement, and decisions based on values (Adesina, 2022; 2025; Dignam et al., 2024; Mei et al., 2025). Green-STEAM initiatives have been associated with improvements in engagement, subject knowledge, innovation readiness, and twenty-first-century skills. However, meaningful implementation requires systems thinking, interdisciplinary collaboration, ethical reasoning, and the capacity of learners to take action on sustainability challenges (Anyolo et al., 2024; Gavrilas & Kotsis, 2025; Khazen et al., 2025; Ölçer-Çevik & Kozaner, 2025; Özdemir-Yılmaz, 2025). Continued research, curriculum development, and teacher professional development are therefore important for preparing learners to contribute creatively and responsibly to sustainable futures.

Artificial Intelligence in Education (AIED) is an interdisciplinary field concerned with the design, use, and evaluation of technologies such as machine learning, natural language processing, and generative AI in education (Hussain, 2025; Wang & Chen, 2025; Zhu, et al., 2025). It differs from the broader field of artificial intelligence because its application is informed by pedagogical theory as well as ethical concerns such as fairness, transparency, and human agency. Much of the existing research, however, focuses on higher education and learner-centred technologies, with comparatively less attention given to school leadership, special education, and the wider educational ecosystem. It is also important to distinguish AIED from related concepts such as educational technology, learning analytics, and AI literacy. Educational technology covers a broad range of digital tools, whereas AIED specifically involves the use of algorithmic processes to support teaching and learning. A further distinction is needed between adaptive learning and personalised learning. Although adaptive systems can adjust

learning experiences algorithmically, meaningful personalisation should also take account of learners' goals, interests, backgrounds, and cultural circumstances (Wang & Chen, 2025; Zhu, et al., 2025). For this reason, successful AIED implementation requires attention to technical, pedagogical, and ethical issues. Important concerns include algorithmic adaptivity, stakeholder configurability, transparency, and the management of risks associated with bias and privacy, while also protecting teachers' professional agency (Gajalakshmi et al., 2026; Hemalatha et al., 2026; Islam et al., 2026; Raza, 2026). Future research would benefit from broader socio-technical approaches that place equity, human dignity, and pedagogical integrity at the centre of AI-supported education.

Indigenous Knowledge Systems (IKS) are difficult to capture through a single universal definition because Indigenous communities and cultures differ considerably. In general, IKS refers to knowledge that is local, community-owned, holistic, adaptive, and passed across generations. It may be expressed through beliefs, values, practices, oral traditions, observation, and lived experience. Current scholarship increasingly treats IKS as a living and relational system connected to land, spirituality, culture, and relationships between people and nature, rather than as a fixed body of knowledge that can be transferred unchanged from one setting to another (Hoppers, 2021; Milanese & Sibilla, 2025). IKS develops within particular cultural and environmental circumstances and remains closely connected to the communities that maintain and practise it. Treating Indigenous knowledge simply as a resource that can be extracted and used to solve externally defined problems can therefore ignore its ethical, cultural, and spiritual foundations. Whereas dominant Western approaches often place emphasis on objectivity and individualism, IKS commonly gives greater attention to reciprocity, stewardship, responsibility, and long-term relationships with the

environment (Bhatia et al., 2025; Teku, 2026). It is also important to distinguish IKS from related concepts. Traditional Ecological Knowledge is primarily concerned with relationships within ecological systems, while IKS can extend to governance, spirituality, health, and social organisation. Local knowledge may exist without a history of Indigenous continuity, while ethnoscience examines culturally based knowledge from an academic perspective. Indigenous Data Sovereignty, on the other hand, concerns Indigenous peoples' rights to control the ownership and governance of their data and territories (Amores & Aguilar, 2026; Milanese & Sibilla, 2025). IKS is commonly transmitted through storytelling, ceremonies, observation, land-based learning, and community participation. Working with such knowledge therefore requires respect for Indigenous self-determination, cultural pluralism, and intergenerational transmission. Future scholarship should pay greater attention to Indigenous governance, fair knowledge partnerships, cultural revitalisation, and the protection of Indigenous intellectual heritage.

Technology integration models help explain the relationship among digital tools, pedagogy, and learning outcomes. Existing frameworks include knowledge-based models such as TPACK, transformative-use models such as SAMR and PICRAT, and technology acceptance models such as TAM and UTAUT (Abar & Almeida, 2025; Choudhury & Dutta, 2024; Trif-Boia, 2023). Each framework highlights a different aspect of technology use. Some focus on teachers' knowledge and instructional decisions, while others examine technology adoption, classroom transformation, or learners' experiences. No single model, however, fully captures the realities of technology integration in classrooms. Effective use of technology depends on the interaction between pedagogy, instructional design, institutional support, and the context in which teaching takes place. Technology integration should therefore be understood as a broader educational process

rather than simply the introduction of a digital tool into an existing lesson. One important limitation of some technology integration approaches is the tendency to regard technology as an additional instructional tool rather than as something that can influence pedagogical and institutional practice. Meaningful integration is more relational, context-dependent, and potentially transformative. The Socio-Ecological Technology Integration model, for example, draws attention to leadership, infrastructure, and institutional policy, while TPACK shows how effective teaching can emerge from the interaction of technological, pedagogical, and content knowledge in authentic learning situations (Crompton, 2026). Although integration models are different from instructional design and digital competence frameworks, the different perspectives can complement one another in practice (Crompton, 2026; Trif-Boia, 2023). Future work should therefore favour holistic, human-centred, and socio-technical approaches that move beyond technological determinism and focus on improving learning, teaching, and sustainable educational innovation.

Contextualisation has become increasingly important in discussions of curriculum and pedagogy. It involves deliberately adapting curriculum content, teaching methods, and assessment to learners' socio-cultural, linguistic, economic, and environmental circumstances (Ajani, 2025; Organisation for Economic Co-operation and Development, 2025). Drawing on situated learning theory, contextualisation makes learning more meaningful by connecting academic knowledge with learners' experiences and practices within their communities (Kulkarni et al., 2025; Shen et al., 2025).

Contextualisation should not be confused with adaptation, localisation, individualisation, or recontextualisation. Rather, it deliberately places knowledge within the shared socio-cultural environment in which learners live and learn and can

influence both curriculum design and classroom practice (Aprilia et al., 2025; Getahun et al., 2024; Paputungan & Siradjang, 2025). Its effective use requires sensitivity to place, flexibility in teaching, respect for disciplinary knowledge, and responsiveness to learner diversity. The OECD Teaching Compass (2025) also presents teachers as important agents of curriculum change, highlighting the role of their professional competence and well-being in building future-ready education. Contextualisation is therefore better understood as a culturally grounded and teacher-led process that promotes meaningful and equitable learning, rather than as an attractive addition to an otherwise standardised curriculum (Paputungan & Siradjang, 2025; Reddy & Revathy, 2024).

The Culturo-Techno-Contextual-Artificial-Intelligence (CTCAI) Pedagogy extends Professor Emeritus Peter Okebukola's Culturo-Techno-Contextual Approach by bringing artificial intelligence into learning experiences that recognise learners' cultural identities, Indigenous knowledge, languages, and local environments (Okebukola, 2020). The framework does not treat AI as culturally neutral. Instead, it assumes that meaningful learning is more likely when technology is connected to learners' identities and everyday experiences. Cultural alignment requires AI-supported learning to recognise local languages, values, and social realities, while contextual intelligence focuses attention on the environmental and socio-economic circumstances in which learning occurs. Learners are not expected simply to accept AI-generated information. They are encouraged to question it, modify it, and adapt it to their cultural circumstances. In this sense, AI becomes part of a participatory process of knowledge construction and decolonisation. Compared with mainstream Artificial Intelligence in Education, CTCAI brings together culturally responsive pedagogy, AI literacy, contextual learning, and postcolonial theory, while treating AI

itself as something that can be examined and reshaped through culture.

Findings from foundational CTCA studies provide initial evidence for these ideas. Culturally grounded and context-sensitive approaches have been associated with better learner engagement, understanding, achievement, retention, and emotional well-being (Jufrida et al., 2025; Nguyen, 2025; Samuel et al., 2023; Sharma, 2025; Xia et al., 2024). Studies applying CTCA principles to AI instruction have also reported improved achievement, better understanding of difficult concepts, and stronger long-term retention compared with conventional approaches (Okada et al., 2025; Sharma et al., 2025). More empirical work is still needed to establish the broader effectiveness of CTC AI, but the framework makes an important contribution by arguing that educational intelligence should remain connected to human culture, ethical values, local circumstances, and contextual relevance.

Linking CTC AI to STEAM Education

The rapid growth of AI and digital technologies has increased the need for educational approaches that can accommodate cultural diversity while addressing sustainability. STEAM education brings Science, Technology, Engineering, Arts, and Mathematics together to develop the critical thinking, creativity, and innovation needed in the twenty-first century. However, many STEAM programmes in the Global South, including those in Africa, continue to draw heavily on models developed elsewhere. When such models give little attention to Indigenous knowledge and local socio-economic conditions, learners may find the learning experience less relevant to their own lives. CTC AI offers a way of addressing this gap by reconnecting STEAM learning with learners' experiences and using AI in ways that support meaningful, equitable, and sustainable learning.

CTCAI builds on Peter Okebukola's Culturo-Techno-Contextual Approach (CTCA), which demonstrated the value of combining cultural responsiveness with technology-supported teaching in science education. CTCAI extends this foundation by placing AI within specific cultural settings rather than treating it as a neutral technology that can be applied in the same way everywhere. Human values remain central to the approach. Cultural alignment encourages the use of local languages, narratives, and values, while contextual intelligence helps teachers and learners relate learning to environmental and social challenges within their communities. STEAM, in this setting, becomes more closely connected to community life and to the problems learners can actually see and experience.

CTCAI also treats learners as active participants in shaping their interaction with AI. Rather than simply receiving technological outputs, learners can question them, modify them, and consider whether they fit their cultural and social circumstances. Such engagement can support ethical awareness, broader understanding, and sustainable forms of innovation. Empirical studies of CTCA interventions across Biology, Bioenergetics, Business Education, Development Studies, elementary Artificial Intelligence instruction, Mathematics, Physics, Public Administration, and science process skills have reported improvements in achievement, engagement, perception, and well-being (Adam et al., 2025; Adekoya, 2023; Awaah et al., 2021; Ayanwale & Puseletso, 2025; Olafare et al., 2025; Ogundowole et al., 2025; Oladejo et al., 2023; Tetteh et al., 2025). Although further research is required to establish the wider evidence base, CTCAI provides a promising pathway for developing STEAM education that is inclusive, culturally responsive, and attentive to sustainability.

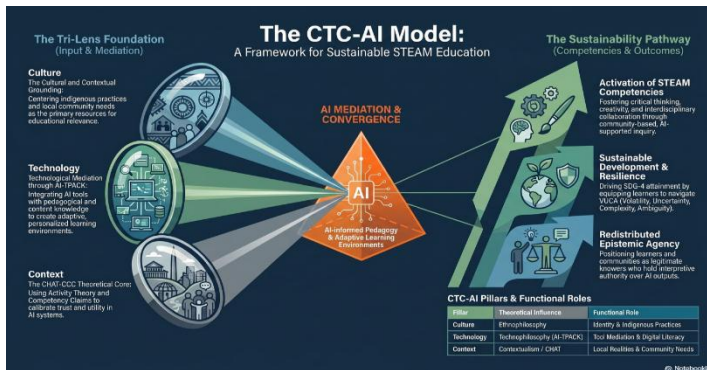


Fig. 1: CTC-AI STEAM Sustainability Model
Source: The Authors (2026)

From Figure 1, the Culturo-Techno-Contextual-AI (CTC-AI) STEAM Sustainability Model is a transformative framework replacing didactic paradigms with a holistic approach to ensure STEAM Education Sustainability. It integrates three lenses: Culture, which centres indigenous "funds of knowledge"; Technology, viewing AI as an "epistemic partner"; and Context, anchoring learning in local socio-economic realities. Operating through a mediational workspace supported by CHAT, TPACK, Connectivism, Connectionism, and Social Constructivism, the model analyses interactions between learners and AI. A pivotal feature is the Redistribution of Epistemic Authority, where students use "epistemic fine-tuning" to compare AI outputs against situated local knowledge, fostering healthy technoskepticism. This synergy cultivates vital STEAM Competencies-innovation, critical thinking, and collaboration-enabling learners to develop system thinking and resiliency. Ultimately, CTCAI ensures education remains inclusive and relevant, fostering long-term human flourishing within increasingly automated, complex, and volatile global landscapes.

Benefits and Implications of CTCAI in STEAM Education

The Culturo-Techno-Contextual Artificial Intelligence (CTCAI) pedagogy offers a different way of thinking about AI-supported learning by placing culture at the centre of meaningful technology integration. Rather than treating culture as an additional factor to be considered after the technology has been introduced, CTCAI regards learners' cultural backgrounds as an important part of the learning process. Building on the Culturo-Techno-Contextual Approach (CTCA), available empirical evidence indicates improvements in academic achievement, conceptual understanding, knowledge retention, and critical thinking, without significant differences associated with gender. When teaching is connected to learners' cultural experiences, CTCAI creates opportunities for more equitable and human-centred engagement than approaches that assume AI can operate effectively without regard to culture.

For teachers, the framework provides a practical basis for using AI as part of teaching rather than simply introducing it as another classroom technology. Its emphasis on contextual intelligence, cultural alignment, and ethical use can help teachers develop learning experiences in which digital tools and Indigenous knowledge complement one another. It also creates opportunities for professional growth by helping educators learn how to design AI-supported activities that are responsive to the cultural, linguistic, and social circumstances of their learners. CTCAI also has implications for curriculum development and educational policy. It offers a framework through which culturally responsive AI education can be developed and adapted to different settings. Curricula that can be configured around local needs and languages provide an alternative to standardised, one-size-fits-all approaches and can contribute to the wider decolonisation of STEM education. Governments can also use such an approach to strengthen AI literacy while supporting technological sovereignty,

particularly by encouraging learners to question, shape, and contribute to technology rather than simply consume it.

Realising this potential will require investment in culturally diverse datasets and assessment approaches that capture meaningful learning rather than technological performance alone. Incorporating local languages and community values into AI-supported education can also contribute to SDGs 4 and 10. In this respect, technological advancement and cultural sustainability need not be competing goals; when carefully integrated, they can support more inclusive, resilient, and human-centred education.

Conclusion

The Culturo-Techno-Contextual Artificial Intelligence (CTCAI) pedagogy provides a culturally grounded approach to sustainable STEAM education. Its central premise is that culture should not be treated as a secondary consideration in the use of AI; rather, it should form part of the foundation on which meaningful learning is built. Evidence from related CTCA work points to improvements in learner outcomes, teacher development, and the broader effort to decolonise educational content and practice. In this sense, CTCAI offers a possible pathway towards greater technological sovereignty. However, the successful implementation of the framework cannot be achieved through technology alone. Persistent challenges such as unequal digital access, algorithmic bias, ethical concerns, and infrastructure costs require sustained policy commitment, institutional support, and changes in educational practice. The particular strength of CTCAI lies in bringing culture, technology, and context together. When any one of these elements is given undue priority at the expense of the others, there is a risk of reproducing forms of epistemic exclusion and algorithmic colonialism. By incorporating Indigenous knowledge and contextual intelligence into AI-supported learning, CTCAI provides a practical way of

advancing SDG Target 4.7. It can help ensure that STEAM education remains inclusive, equitable, culturally meaningful, and responsive to the sustainability challenges of an increasingly digital and automated world.

Recommendations

The implementation of CTCAI is likely to face several related challenges, particularly in ensuring that its benefits are accessible and sustainable. One of the most immediate concerns is the digital divide. In many African settings, limited internet access, unreliable connectivity, and differences in digital infrastructure can widen existing educational inequalities. Practical responses should therefore include affordable and low-bandwidth delivery options, such as WhatsApp-based learning platforms and zero-rated educational services, where feasible. Teacher preparedness is another important concern. Having basic technical skills does not necessarily mean that teachers are prepared to use AI effectively from pedagogical or ethical perspectives. Professional development should therefore go beyond short workshops or one-off technology training. Teachers need sustained, practice-oriented support that enables them to develop contextual intelligence and make informed decisions about adapting AI tools to local cultural and linguistic conditions. Cultural mismatch within mainstream AI systems is another concern. AI systems trained largely on Western-centred datasets may overlook or misrepresent Indigenous knowledge, local experiences, and community narratives. Addressing this problem requires greater attention to culturally diverse datasets, multilingual AI models, and systems that are validated within the communities in which they are used. Such measures can help ensure that technological development remains relevant to learners' actual experiences.

Ethical and sustainability issues also require careful attention. Algorithmic bias, data privacy, and the risk of making learning

overly impersonal cannot be ignored. Ethics-by-design approaches should therefore include transparent governance arrangements, regular assessments of algorithmic bias, and assessment practices that value meaningful learning processes rather than technological outputs alone. The cost of infrastructure and the limited investment in educational technologies also raise questions about the long-term sustainability of CTCAI. Continued government commitment, institutional support, and strategic partnerships will be necessary.

AI resources should increasingly be regarded as part of educational infrastructure rather than as temporary technology projects. Their development and use should also take environmental sustainability into account. In settings where resources are limited, lightweight and task-specific AI models may provide more practical alternatives to highly resource-intensive systems. Ultimately, the potential of CTCAI will depend on how well it becomes part of national curricula, institutional practices, and broader educational values that support inclusion, cultural sustainability, and long-term human development.

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