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Advancing Global Science, Technology, Engineering and Mathematics (STEM) Education through Innovation, Artificial Intelligence, Sustainability and Climate-Smart Practices

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Abstract **Review Article**

The complexity of contemporary global challenges demands a re-imagined STEM education that is innovative, intelligent, sustainable and climate-responsive. This paper conceptualizes the advancement of global STEM education through the convergence of four critical drivers: Creativity/innovation, Artificial Intelligence (AI), sustainability, and climate-smart practices. Drawing on Torrance's Creativity Theory, UNESCO's Education for Sustainable Development (ESD) for 2030 framework, and Systems Thinking Theory, the paper argues that STEM must transcend rote content transmission to become a transformative, action-oriented enterprise. It synthesizes insights from four complementary frameworks: the CREATIVE-STEM Framework, the AI-STEM Global Enhancement Framework, the SUSTAIN-STEM Model, and the CLIMATE-SMART Transnational STEM Framework. Collectively, they propose a unified pathway that embeds curiosity-driven inquiry, design thinking and artistic integration; leverages AI for adaptive learning, intelligent tutoring, smart assessment and teacher augmentation; and repositions STEM as a vehicle for solving real-world sustainability and climate challenges through localized context, green innovation, and cross-border collaboration. The paper examines implications for curriculum redesign, establishment of innovation hubs, green laboratories and makerspaces, ethical and human-centred AI adoption, and the pivotal role of teacher training institutions in producing sustainability and climate-literate STEM teachers. It addresses barriers such as curriculum rigidity, infrastructural deficits, and inequitable access with strategies including open educational resources, intercontinental partnerships, and inclusive pedagogy. The paper concludes that advancing global STEM education requires moving from siloed STEM to integrated, climate-smart STEM for sustainable development to accelerate the achievement of SDG 4 and SDG 13.

Keywords: Global STEM Education, Creativity/Innovation, CREATIVE-STEM Framework, Artificial Intelligence, AI-STEM Framework, Sustainability, SUSTAIN-STEM Model, Climate-Smart Practices, CLIMATE-SMART Framework.

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INTRODUCTION

Science, Technology, Engineering and Mathematics (STEM) education is globally recognized as a key driver of innovation, economic growth and sustainable development. According to UNESCO (2017; 2020), STEM is an interdisciplinary approach

that fosters critical thinking, problem-solving and innovation, while education is described as a fundamental instrument for human development and global transformation. However, conventional STEM education has largely remained focused on disciplinary knowledge acquisition and technical competence. Possessing knowledge alone is insufficient, as a learner may understand principles of electricity yet be unable to develop affordable solutions for a community problem, or master mathematical formulas without applying reasoning to environmental and societal challenges. Modern problems like climate change, biodiversity loss, food insecurity, energy transitions and technological disruption cannot be effectively addressed through lonely disciplinary knowledge. This limitation therefore creates the imperative for a re-imagined STEM that equips learners with the dispositions to examine problems, evaluate evidence, collaborate to develop novel, and practical solutions.

This imperative is further intensified by the fourth industrial revolution, which has made creativity and Artificial Intelligence non-negotiable enablers of that re-imagined STEM (Ayua et al., 2026c; Ayua et al., 2026d). Building on the need to move beyond memorization, Bybee (2023) and Ayua et al. (2023) argue that STEM must incorporate creativity defined as fluency, flexibility, originality and elaboration, allowing learners to transform theoretical knowledge into practical solutions. Complementing this creative turn (Ayua, 2019a); Ayua & Eriba, 2023), Artificial Intelligence — defined as computer systems that learn from data to perform human-like tasks such as visual perception, speech recognition and decision-making (Luckin et al., 2016; Kaplan & Haenlein, 2019) — offers powerful techno-pedagogical leverage through adaptive learning, intelligent tutoring and smart assessment that adapts to individual needs (Terhemba et al., 2026). Importantly, as emphasized in recent scholarship, AI augments rather than replaces the teacher. Yet, as the Nigerian context illustrates where the Federal Ministry of Education (2019) positions Science and Technology Education strategically, real transformation hinges not on policy alone but on classroom practices that encourage questioning, experimentation, design and learning from failure, despite uneven access to laboratories and maker spaces.

While creativity and AI provide the pedagogical tools, sustainability and climate change provide the most compelling content and good framework for applying them. In other words, if innovation and AI answer how we should teach STEM differently, sustainability answers why and what for. Sustainability seeks to balance environmental, social and economic resources to meet present needs without compromising future generations, which is central to Sustainable Development Goal four (SDG 4) on quality education and SDG 13 on climate action. This calls for functional, green pedagogical education that is universally accessible (Ayua et al., 2022; Fox & Wogowitsch, 2021). Climate change is basically transnational since greenhouse-gas emissions, atmospheric processes, ocean systems and water resources defy international boundaries, demanding integrated scientific inquiry, technological innovation, engineering design and mathematical modelling. As Padhra and Tolouei (2023) advocate embedding climate education across programmes, Ma and Chen (2023) caution that responses in the Global South must be sensitive to local economic and institutional conditions. Consequently, climate-smart STEM education emerges as a bridge that connects local realities, such as flooding in Makurdi or Lokoja, to global knowledge networks through virtual laboratories, remote sensing and collaborative platforms, though disparities in connectivity, electricity and funding still limit participation.

It is precisely at the intersection of these pedagogical enablers and sustainability imperatives that the current gap in practice becomes most evident. On one hand, STEM remains **siloed** (taught/learnt in isolation without collaboration with other subjects, systems or people), exam-driven and disconnected from real-world problems; on the other, opportunities for international collaboration remain limited and unevenly distributed. To address this yawning gap, this paper proposes an integrated pathway to advancing global STEM education through innovation, artificial intelligence, sustainability and climate-smart practices.

THE PROBLEM

STEM education in its ideal form is supposed to make individuals skilful for action towards achieving the Sustainable Development Goals - no poverty, zero hunger, good health, quality education, clean water, clean energy, sustainable cities, climate action and partnership for the goals. However, there is a yawning gap between policy and practice for holistic implementation. STEM is traditionally taught as a body of knowledge in isolation from sustainability and real-world challenges like climate change, energy and water conservation. This isolation, coupled with one-size-fits-all, teacher-centred and examination-driven approaches that emphasize memorization instead of creativity and problem-solving, limits students' ability to connect STEM knowledge to solving real-world problems (Anwar et al., 2023; Ayua et al., 2023, Ayua et al., 2025). The fourth industrial revolution [**4IR** = rapid technological change where physical, digital and biological systems merge through AI, robotics, **IoT** (Internet of Things), big data, and automation to transform how we live, learn and work] and increasing application of artificial intelligence, machine programming and other emerging technologies demand critical, creative and techno-pedagogical competencies, yet quality STEM education remains poor. This is marked by unequal access to STEM learning, inadequacy of laboratories, resources and qualified teachers especially in rural and disadvantaged communities in the Global South (Ayua et al., 2026f; Jaya et al., 2026). Climate change, being transnational, requires integrated inquiry but STEM disciplines are taught as disconnected content while climate issues are treated as general environmental topics. Integrated STEM projects remain dependent on teacher capacity, curriculum structures and funding, and disparities in connectivity, electricity and devices prevent participation in digitally mediated international experiences (McLure et al., 2022; Ma & Chen, 2023). There is no unified framework that intentionally organizes innovation, AI, sustainability and climate-smart practices for global STEM education; and hence the essence of this conference on "advancing global Science, Technology, Engineering and Mathematics (STEM) education through innovation, artificial intelligence, sustainability and climate-smart practices".

PURPOSE OF THE PAPER

The purpose of this paper is to advance global STEM education through innovation, artificial intelligence, sustainability and climate-smart practices with the specific objectives to:

1. Conceptualize frameworks that connects STEM knowledge, sustainability challenges and climate-smart problem-solving to make STEM more relevant, interdisciplinary and inclusive.
2. Examine how creativity and AI-supported pedagogies can enhance teaching, learning and assessment in STEM globally.
3. Demonstrate how local environmental realities can be connected to global knowledge networks.
4. Provide implications for equitable, integrated, and sustainable global STEM education in the 21st century.

THEORETICAL ANCHORAGE

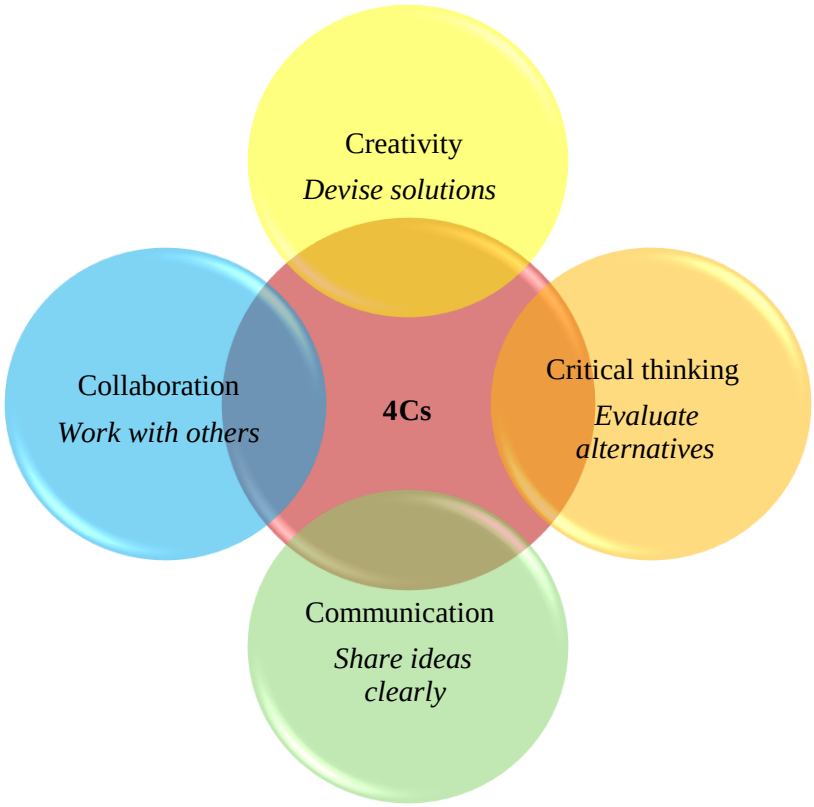
This anchored on 6 theories as follows:

A. Torrance's Creativity Theory -STEM as creative enterprise

Torrance (1974) Creativity Theory conceptualises creative thinking as a multidimensional process linking fluency, flexibility, originality, and elaboration. Fluency entails generating multiple ideas, flexibility mirrors the ability to consider various tactics, originality concerns creating fresh ideas, and elaboration requires advancing and refining those ideas. The theory is relevant to STEM education because effective STEM learning requires learners exploring alternatives, solving open-ended problems, designing solutions, and improving their ideas. Consequently, the theory provides useful basis for understanding and assessing how STEM learning experiences could foster learners' creative thinking.

Figure 1

The 4Cs of the 21st-Century Skills



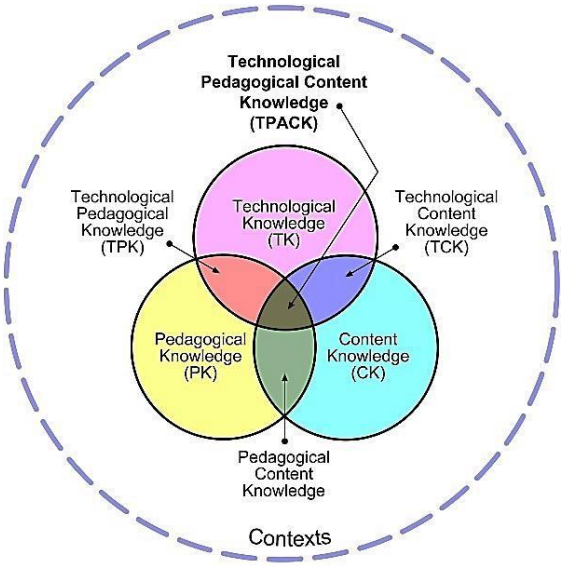
As contained in Figure 1, each of the Cs has a shared work of solving STEM problems, rather than separate, standalone skills. It shows that STEM problems are not only solved by committal to memory, but also via learners drawing on all the four competencies at once creating ideas, evaluating them critically, articulating them clearly, and building abilities with others.

B. Technological Pedagogical Content Knowledge (TPACK) Framework

The TPACK framework is a theoretical framework developed by Mishra and Koehler (2006). The framework explains the knowledge teachers need to integrate technology effectively into teaching. The framework consists of three forms of knowledge relevant for effective and efficient teaching as presented in Figure 2.

Figure 2

The Schematic Representation of TPACK Framework (Mishra & Koehler, 2006)



As show in Figure 2, Technology Knowledge (TK) is being knowledgeable about varieties of technological tools ranging from the basic, such as pencil and paper, to the most sophisticated, such as the world wide web, digital video, interactive white board and computer programs. Content Knowledge (CK) is the information about a specific topic that could be covered in a course or lesson. Educators therefore need background knowledge on the subjects they planned to cover and an understanding of how different types of knowledge are taught. Pedagogical Knowledge (PK) includes skill the in the classroom administration, students' evaluation, lesson planning and students naming. Pedagogical Content Knowledge (PCK) is the subjects' matter; experts gain for instructional purpose. Knowledge of both the subject matter and pedagogical practices necessary for effective teaching is PCK and its subject specific.

Technological Content Knowledge (TCK) is being familiar with the ways in which modern technologies can be used to create alternative representations of existing information. It means that educators can appreciate the power of technological tool such AI to change their students' approaches to learning within a subject area. Technological Pedagogical Knowledge (TPK) can describe educators who are well versed in the way in which modern technology can be applied to the classroom and who recognise that these tools have the potential to alter traditional or conventional pedagogy. Technological Pedagogical Content Knowledge (TPACK) for effective teaching in any subject area, there can be a firm grasp of the educational content of technical tools at teacher's disposal. Teachers can have an intrinsic awareness of the relationship between the three pillars of knowledge, as evidenced by their utilization of successful pedagogical practice and technology resources in the STEM classroom for development of learners' 21st-century skills (CK, PK, TK).

The TPACK Framework provides a theoretical foundation for the integration of AI in STEM education by emphasizing the intersection of technological, content and pedagogical knowledge. This suggests that effective AI-supported STEM education requires teachers not only to have content and pedagogical knowledge but to be competent in

handling technologies such as AI to support STEM instruction.

C. UNESCO ESD for 2030 Framework - STEM for sustainable development

The UNESCO (2020) Education for Sustainable Development (ESD) for 2030 framework, advocated by UNESCO as an evolution of the UN Decade of ESD (2005-2014), postulates that education must advance knowledge, skills, values, attitudes and behaviours for sustainable development. It assumes that learning should be transformative and action-oriented to allow learners to address present-day sustainability challenges. Its implication is that it provides the philosophical validation for reorienting STEM education from sheer disciplinary knowledge transmission to a vehicle for sustainable advancement and the achievement of the SDGs.

D. Systems Thinking Theory - Interconnectedness of STEM, society and planet

Systems Thinking Theory, founded on Bertalanffy (1968) and popularized by Senge (1990), holds that multifaceted problems must be understood through the interactions and mutuality among system components rather than in isolation. It is a holistic approach for examining complex difficulties and systems that focus on the interactions among system components and the patterns that emerge from those interactions (York et al., 2019). It assumes that sustainability problems such as climate change, energy insecurity and water scarcity are interrelated systems. Its implication is that it offers the conceptual lens for strengthening STEM education, needing that STEM be taught as an interdisciplinary enterprise where scientific, technological, environmental, social and economic systems relate.

E. Constructivist Learning Theory

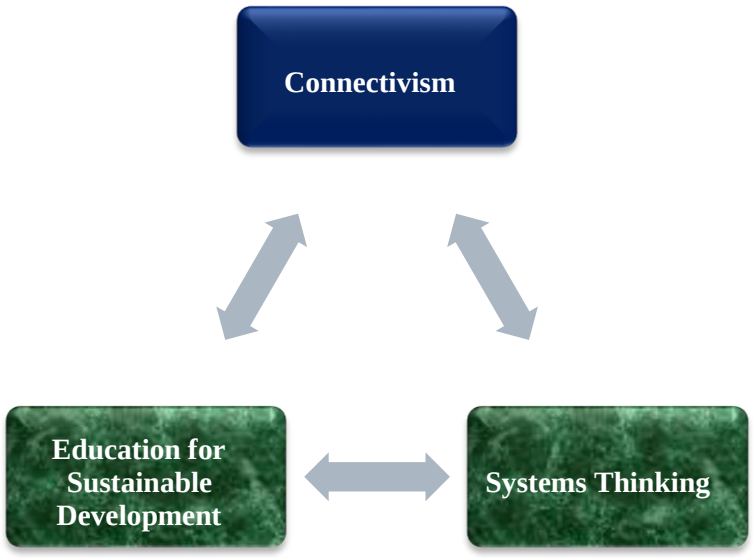
Constructivist Learning Theory propounded by Piaget (1936) and Vygotsky (1978) asserts that learners actively construct knowledge from experience. It assumes that meaningful learning occurs through active engagement with real-world problems. Its implication is that it provides the pedagogical basis for strengthening STEM education, suggesting that sustainability-based problem-solving enables learners to meaningfully construct STEM knowledge and competencies essential for sustainable development.

F. Theory of Connectivism

Siemens' (2005) Theory of Connectivism as presented in Figure 3 conceptualises learning as the formation and maintenance of connections among people, information sources, digital environments and knowledge networks. Connectivism is vital to transnational STEM education because digital networks allow learners to access information and collaborate beyond the boundaries of their classroom and country. Learners can connect to climate datasets, scientific publications, remote laboratories, experts, teachers and international peers through climate-smart STEM education. This theory explicates why knowledge cannot be treated as something located exclusively in a learner. Climate knowledge can be shared across scientific institutions, environmental monitoring systems, communities, governments, technological platforms and international communities.

Figure 3

Theoretical Framework



Learning constitutes knowing where to source for vital knowledge, how to evaluate it, how to connect it to another knowledge, and how to use it ethically. Studies on AI-supported science education and digital classrooms reinforce the modern relevance of technology-mediated learning and digital participation in STEM education (Ayua et al., 2026; Terhemba & Ayua, 2026). As shown in Figure 3, Education for Sustainable Development (ESD) highlights knowledge, competencies (Ayua, 2019b), values and action for solving social, environmental and economic problems (Ayua & Terhemba, 2025). Its importance to this framework lies on systems thinking, participation, responsibility and action. Climate-smart STEM education operationalises ESD by changing climate challenges into authentic STEM problems. Learners do not learn what climate change is but they can examine or explore local evidence, examine alternative responses, design solutions and consider the implications of their decisions. According to Stouthart et al. (2023) preparing teachers to use socio-scientific problems like climate change is central to developing sustainability-based pedagogical ability. STEM-ESD integration also shows a growing attention to connecting STEM learning with sustainability challenges (Habibaturrohmah et al., 2023). Climate change requires interacting systems instead of isolated variables since temperature, rainfall, agriculture, water, energy, health, infrastructure and economic activity interact in complex ways. Systems thinking as presented in Figure 3 encourages learners to recognise relationships, feedback loops, interdependencies and unintended consequences. Making stronger therefore, the conceptual basis of transnational STEM education because learners can compare how similar climate processes interact with different social, geographical and technological systems. Together, Connectivism, ESD and systems thinking in Figure 3 create complementary explanations: connectivism which is the network through which knowledge is accessed and shared, while ESD is the sustainability-based purpose of learning and systems thinking shows how learners understand interconnected climate systems.

Pillar 1: Promoting Global Stem Education through Creativity/Innovation

This pilar is presented as follows:

A. Why creativity is non-negotiable for STEM Education?

Creativity is non-negotiable for STEM Education because knowledge alone is insufficient for innovation, economic growth and sustainable development. As Bybee (2023), Ayua et al. (2023) and Henriksen (2024) argue, STEM is beyond acquiring disciplinary knowledge in Science, Technology, Engineering and Mathematics to include generating new, original and useful ideas through imagination, fluency, flexibility and problem-solving. A learner may understand electricity yet fail to develop an affordable solution for a community problem, or master mathematical formulas without applying them to unfamiliar technological or societal issues. Modern challenges like climate change, waste management or energy use rarely appear in isolated categories; they demand integrated solutions where learners question, design, test, fail, reflect and refine ideas through engineering design. This aligns with Torrance's theory of fluency, flexibility, originality and elaboration, and the 4Cs framework of creativity, critical thinking, communication and collaboration, which OECD (2024) and PISA 2022 recognize as complementary to performance in science and mathematics. Pont-Niclòs et al. (2024) also show that scientific creativity sustains engagement and career intention in STEM.

In developing countries like Nigeria, where the Federal Ministry of Education (2019) positions Science and Technology Education strategically, transformation requires more than policy. Yet, as Beghetto and Kaufman (2024) and OECD (2023) note, conventional exam-driven, content-heavy curricula, assessment constraints, teacher capacity gaps, and uneven access to laboratories and maker spaces restrict creativity. Nevertheless, without embedding creativity, STEM remains knowledge reproduction rather than knowledge-creation, failing to produce innovators capable of solving real-world problems.

B. The CREATIVE-STEM Framework

The Creative-STEM model as presented in Figure 4, involves: Curiosity, Real-world problem solving, Design thinking, Art-Tech integration, Teacher facilitation, Innovation hubs, Value of failure, and Equity.

Figure 4

The CREATIVE-STEM Framework

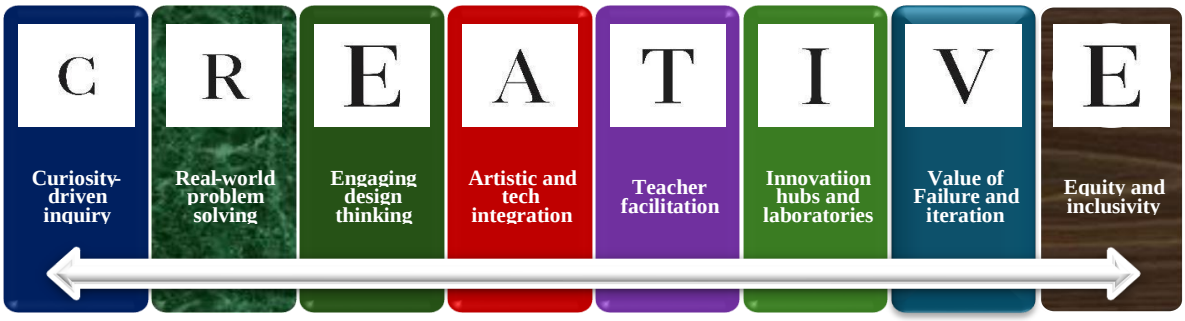


Figure 4 treats Creativity as a pedagogical core, with each letter carrying a principle that is meant to be actionable rather than aspirational from starting lessons with a genuine "what if" question, through making sure innovation opportunities aren't quietly reserved for well-resourced schools.

Components of the CREATIVE-STEM Framework

These components are further presented in their themes.

Figure 5

C – Curiosity-Driven Inquiry

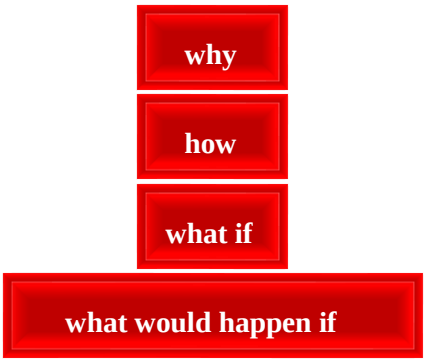


Figure 5 point of creative STEM learning explains that teachers may encourage learners to ask "why," "how," "what if" and "what would happen if." questions. Inquiry activities can begin with familiar local phenomena such as water quality, waste management, energy use, agricultural production or transportation.

R – Real-World Problem Solving explicate that STEM learning may connect classroom concepts with authentic problems. Students could be challenged to identify problems within their communities and develop evidence-based solutions. This approach may help learners recognise the usefulness of STEM knowledge beyond examinations.

Figure 6

E – Engaging Design Thinking

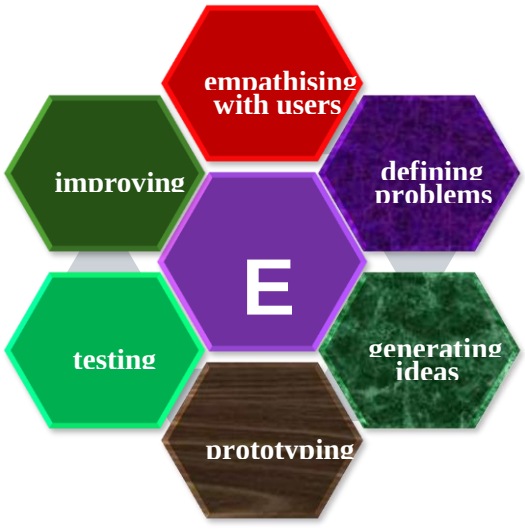


Figure 6 shows that in STEM education, students can use these processes to develop solutions while learning disciplinary concepts.

A – Artistic and Technological Integration explains that an integration of arts with STEM creates opportunities for communication, visualisation, creativity and interdisciplinary thinking. This does not mean turning every STEM lesson into an art lesson. Rather, artistic representation, storytelling, visual design, music, cultural knowledge and creative expression can enhance technological and scientific learning.

T – Teacher Facilitation of Creative Pedagogy: Means that teachers are central to the framework. Their role is to design environments in which students can explore ideas while maintaining academic rigour. Effective teachers ask productive questions, encourage evidence-based reasoning and provide feedback that helps learners improve their ideas.

I – Innovation Hubs and Laboratories: Highlight that schools may establish innovation spaces where learners can experiment, design, and team-work. These spaces do not certainly require costly equipment. A well-organised classroom corner with recycled materials, basic tools, computers or improvised resources can function as a small innovation laboratory.

V – Value of Failure and Iteration: Creative STEM necessitates a different understanding of failure. When experiments do not produce the probable result or prototypes fail, learners should be motivated to investigate why. Thus, failure becomes information which guides perfection. This principle is key in engineering, where solutions emerge by repeated testing and modification.

E – Equity and Inclusivity in Creative Access: Creativity can be accessible to all learners regardless of gender, socioeconomic background, location or disability. Global STEM education avoids creating learning situation where bias is practiced.

How the Framework Promotes International STEM Education

The CREATIVE-STEM model aids global STEM education by promoting mutual competencies like: creativity, problem solving, collaboration, inquiry and design; while permitting the capabilities to be applied to problems that are meaningful within different cultural and ecological contexts. This tactic is imperative because STEM education is not experienced homogeneously across nations. Its priorities and practices are designed by historical, cultural, socioeconomic and political circumstances (Mudaly & Chirikure, 2023). Thus, learners in Nigeria may design low-cost water purification systems, solar energy solutions or agricultural technologies. Learners elsewhere could explore coastal erosion, urban transport, renewable energy or digital inclusion. The basic creative procedure is transferable even when the problem differs. This context-sensitive style braces meaningful STEM learning while knowing cultural variances (Kier & Johnson, 2022). This may also aid world-wide team-work by digital platforms, where learners exchange ideas, compare data and jointly devise solutions to global problems.

Educational Implications of the CREATIVE-STEM Model

1. **Curriculum Redesign:** Shift from content-only to inquiry, project-based and interdisciplinary learning; emphasize creativity, critical thinking, collaboration and problem-solving; use performance-based assessment alongside exams.
2. **Teacher Professional Development:** Move beyond one-off workshops to sustained, hands-on training in inquiry-based, problem-based, design thinking, low-cost experiments, digital/AI and inclusive assessment.
3. **Institutional Support:** Provide laboratories, digital resources and funding, but adapt to local realities using recycled materials and prudent innovation.
4. **Global Partnerships:** Connect schools, industry and research via virtual laboratories and online communities to merge technical expertise with local knowledge.

Constraints to Implementation

1. **Cultural Barriers:** Teacher-centred norms vs learner-centred creativity; dominance of standardized examination culture.
2. **Infrastructural Barriers:** Scarce laboratories, digital tools and materials, especially in rural schools.
3. **Systemic Barriers:** Teachers trained in siloed (isolated) subjects, limited preparation for interdisciplinary teaching; uncritical copying of Global North models without contextualization.

Strategies for Combating Constraints

1. **Affordable, Context-Sensitive Methods:** Use improvised/recycled materials for practical activities like water filtration, solar energy, irrigation and bridge construction.
2. **Creative Teacher Capacity:** Train teachers in designing, testing and refining solutions with limited resources.
3. **University-Industry-School Linkages:** Universities offer mentorship and lab access; industry provides equipment, internships and real-world problems.
4. **Policy and Assessment Reform:** Promote equitable access for rural schools and reform assessment to value reasoning, originality and improvement (Ayua et al., 2026f).

PILLAR 2: ENHANCING GLOBAL STEM EDUVATION LEVERAGING ARTIFICIAL INTELLIGENCE

This pilar is presented as follows:

A. Is AI an enabler or a replacement?

AI is an enabler, not a replacement in global STEM education. While AI is defined as computer systems that learn from data to perform human-like tasks such as visual perception, language use, decision-making and creating new content (GenAI) (Luckin et al., 2016; Kaplan & Haenlein, 2019), its pedagogical value lies in augmenting rather than substituting teachers. As Terhemba and Ayua (2026) emphasize, AI systems can only support and not replace the teacher.

STEM education, which integrates Science, Technology, Engineering and Mathematics to foster critical thinking, problem-solving and innovation for SDGs, faces persistent gaps between policy and practice: unequal access, inadequate resources, high student-teacher ratios and teacher-centred rote memorization (Ayua, 2019). The AI-STEM Global Enhancement Framework conceptualizes AI around four pillars — adaptive and personalized learning that diagnoses needs and differentiates pace, intelligent tutoring and support available anytime, smart assessment and analytics that identify misconceptions and provide immediate feedback, and teacher augmentation for lesson planning, materials and assessment.

This is grounded in the TPACK theoretical framework (Mishra & Koehler, 2006), which requires intersection of technological, pedagogical and content knowledge. Trends from 2020-2026 show a shift toward generative AI, chatbots and personalized systems (OECD, 2025), yet UNESCO (2026) calls for a human-centred approach. Challenges of infrastructure deficits, electricity, internet, data privacy, algorithmic bias and teacher readiness, especially in rural Nigeria, mean AI cannot autonomously deliver quality education. Instead, when guided by equity, inclusivity, ethics and global collaboration, AI scales access, bridges abstract to concrete learning, and enhances teacher effectiveness, making inclusive, and quality STEM education possible.

B. The AI-STEM Global Enhancement Framework

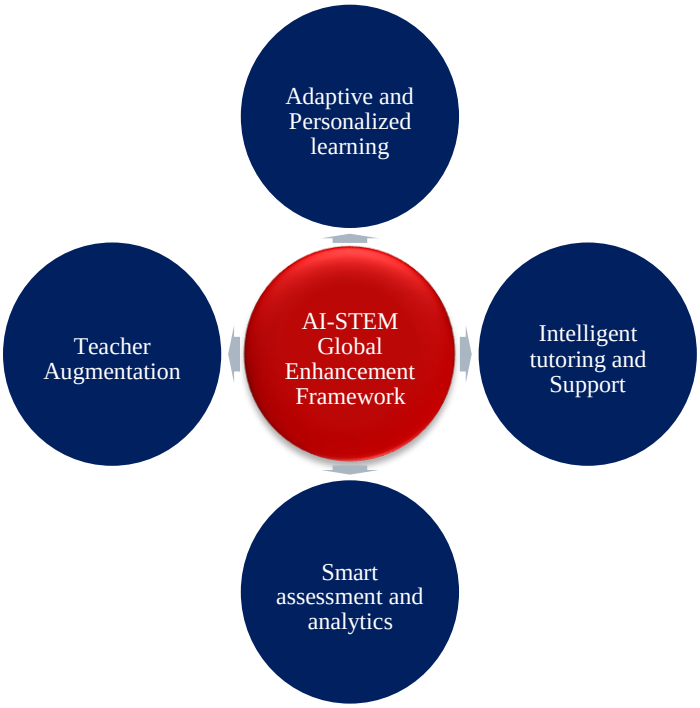
The Rationale for the framework, core pillars, and cross-cutting themes and how the framework will enhance worldwide STEM education, are discussed as follows:

Rationale for the framework

The rapid development of AI systems has created new and endless possibilities for addressing persistent challenges in STEM education. The AI-STEM Global Enhancement Framework is for explaining how AI can be integrated into STEM education to improve learning outcomes and promote equitable access to quality STEM education across geographical boundaries. The framework conceptualizes AI integration around four pillars as shown in Figure 7. These core pillars of AI-STEM Global Enhancement framework are held together and operate within the cross-cutting principles of equity, inclusivity, ethics and global collaboration.

Figure 7

AI-STEM Global Enhancement Framework



As show in Figure 7, adaptive and personalized learning for traditional classroom instruction often presents the same learning activities to all categories of students despite their difference in prior knowledge, learning pace, attitude and learning abilities. AI can address this pedagogical challenge by modifying learning experiences according to the individual characteristics, needs and learning abilities of learners (Ayua et al., 2026b; Jomen & Ayua, 2026; Parsakia, 2023). Within STEM education, adaptive AI systems can diagnose student learning needs and provide additional instruction, examples, simulations or practice activities. Learners who show higher order cognitive abilities can be exposed to more complex problems. This creates differentiated learning experiences for learners at their appropriate learning pace and moves STEM education towards students centred approach. Intelligent tutoring and support show that AI systems have the ability to provide learners with instructional assistance, explanations, guidance and feedback at any day and time during the learning process.

AIbased intelligent tutoring systems can simulate some functions traditionally performed by human teachers such as responding to questions. This pillar is important because STEM learning involves abstract concepts and complex problem-solving processes. This pillar emphasizes the ability of AI to augment teaching and learning at any point along the learning process.

Smart assessment and analytics AI systems can be used for the collection, analysis and interpretation of learner assessment data to improve teaching and learning. AI systems can analyse student assessment and identify patterns of errors, misconceptions and provide immediate feedback. In STEM education, learners are prone to misconceptions on scientific principles or mathematical procedures. AI can diagnose learners through assessment to provide information about these misconceptions. The teacher can then modify instruction to provide an intervention. Teacher augmentation represents the use of AI to enhance and support teachers' instructional responsibilities. Teacher responsibilities such as lesson planning, preparation of instructional materials, assessment construction, and analysis of learner performance and academic development. In STEM education teachers may adopt AI to generate differentiated learning experiences, develop problem-solving activities, formulate assessment questions among others. It is important to emphasize that AI systems can only support and not replace the teacher (Terhemba & Ayua, 2026).

Regarding the cross-cutting themes, equity can ensure that the benefits of AI supported STEM education are available to learners irrespective of geographical location, gender, socioeconomic status or disability. This framework will ensure equal access to STEM education. It will address existing biases and promote fairness across all categories of learners. Inclusivity may focus on designing AI-supported STEM learning activities that accommodate diverse needs, abilities and backgrounds of learners. AI can be utilized as a tool for enhancing the meaningful participation of learners despite the differences that exists between them. Ethics could do with the moral principles that guide the integration of AI in STEM education. The framework is built on responsible use of AI to foster core academic and moral values of honesty, responsibility, integrity and data privacy (Ayua & Gamat, 2018; Ayua & Kwagh, 2026). The framework promotes a human centred approach to the use of AI where AI is used as a supportive tool and not to replace the teacher which borders on irresponsible use. Collaboration among educators, researchers, international organizations, educational institutions, governments and technology developers can facilitate the making of policies, the exchange of knowledge, pedagogical practices and digital resources. Such global collaboration is important for advancing equity in global STEM education in line with Sustainable Development Goal 4.

How the Framework could Enhance Worldwide STEM Education

The AI-STEM Global Enhancement Framework may enhance worldwide STEM education by providing an integrated approach through artificial intelligence which can improve the quality, accessibility, efficiency and inclusiveness of teaching and learning. Rather than viewing AI as a replacement for teachers, the framework can be a complementary technology that supports learners in learning and teachers in teaching. The framework promotes personalized STEM learning and expands access to quality all-round academic support. The framework also strengthens assessment and learning analytics and enhances teacher effectiveness. The work of teachers is often times very bulky for them to do and this can reduce teacher effectiveness and efficiency. AI systems can support teachers in carrying out several tasks at a time including lesson and assessment planning and sourcing for instructional materials. The framework provides an opportunity for access to quality STEM education across local, national and international boundaries.

Educational Implications of the AI-STEM Global Enhancement Framework

1. **Curriculum Integration:** Integrate AI literacy as a 21st-century skill into STEM

curriculum to equip learners to understand, use and responsibly interact with AI technologies.

2. **Teacher Professional Development:** Successful implementation depends on teachers. Ministries and teacher education programs must provide continuous training in AI competency alongside pedagogical and content knowledge (TPACK), including ethical use.
3. **Infrastructure and Policy:** Requires reliable electricity, internet, devices, adaptive platforms and secure digital environments. Governments must invest in rural infrastructure and enact policies for responsible AI use.
4. **Global Partnerships:** International collaboration enables sharing of expertise, technological innovations and digital resources for equitable adoption

Constraints to Implementation

1. **Infrastructural Deficit:** Full-scale implementation requires vast infrastructure — electricity, connectivity, devices, ICT facilities — largely unavailable in rural and developing areas; high cost widens urban-rural disparities.
2. **Ethical Concerns:** Lack of transparency, threats to academic integrity, data privacy, security risks in collection/storage/sharing of students' data, and algorithmic bias reproducing gender and socio-economic inequalities (Ayua & Kwagh, 2026).
3. **Equity and Inclusivity Gap:** Lack of access to devices, internet and digital competency in countries like Nigeria limits adoption and can worsen inequalities (Ayua et al., 2026a; Ayua et al., 2026b).
4. **Human-Centred Risk:** Trend toward generative AI and chatbots (OECD, 2025) raises risk of seeing AI as teacher replacement rather than augmentation, contrary to UNESCO (2026) and TPACK (Mishra & Koehler, 2006).

Strategies for Combating Constraints

1. **Public-Private Partnerships (PPP)**: Governments provide policy and infrastructure; private tech companies provide innovations, expertise and financial resources.
2. **Open Educational Resources (OER):** Reduce dependence on expensive materials by making AI-adapted resources freely accessible, adaptable to learners' needs, language and level.
3. **Low-Cost Digital Tools:** Prioritize mobile-based, offline-capable and low-bandwidth solutions for rural contexts (Ayua et al., 2026e)
4. **Capacity Building:** Continuous training for teachers and students in technological, digital and ethical competencies to ensure effective and human-centred use.
5. **Policy for Ethics and Equity:** Enact clear policies on data privacy, bias mitigation, academic integrity and inclusive design to ensure AI amplifies human work while preserving academic values (Terhemba & Ayua, 2026)

PILLAR 3: STRENGTHENING UNIVERSAL STEM EDUCATION VIA SUSTAINABILITY

This pilar is presented as follows:

A. Why Repositions STEM education for Sustainability (SDG 4 and SDG 13)?

Repositioning STEM education for sustainability is imperative because traditional STEM taught as isolated bodies of knowledge limits learners' ability to connect knowledge to real-world problems like climate change, energy, water and waste (Tarlochan et al., 2025). Sustainability, defined as meeting present needs without compromising future

generations, balancing people, planet and profit (Harvey et al., 2022; Drury et al., 2023), requires a paradigm shift from content acquisition to impact-driven learning.

This repositioning directly advances SDG 4 - Quality Education and SDG 13 - Climate Action. SDG 4 demands inclusive, equitable quality education that ensures learners acquire knowledge, skills, values and attitudes for sustainable development through cognitive, socio-emotional and behavioural dimensions. Universal STEM, accessible irrespective of geography, gender or disability (Kelley & Knowles, 2016), becomes functional when it fosters creativity, problem-solving and innovation for sustainable lifestyles (Ayua et al., 2023a). SDG 13 calls for improved education, awareness and capacity building for climate action.

B. The SUSTAIN-STEM Model its DIMENSIONS

The SUSTAIN-STEM Model provides the framework: Systems thinking sees challenges as interconnected; Use of local context links STEM to community and indigenous knowledge; Sustainable innovation uses design thinking to develop green technologies; Teacher capacity, Assessment for impact through projects not just exams, Inclusivity, and Networking among schools, industries and governments. This approach transforms learners from passive recipients to active designers. The seven dimensions of the model are represented by "SUSTAIN", which includes: S (Systems thinking), U (Use of local context), S (Sustainable innovation), T (Teacher capacity), A (Assessment for impact), I (Inclusivity), and N (Networking). These are stated as follows.

S - Systems thinking: Sees sustainability challenges are being complex and interconnected rather than isolated problems. Issues such as climate change, water, energy and waste involve interactions among environmental, social, technological and economic systems. With the SUSTAIN-STEM Model, systems thinking involves presenting learners with authentic sustainability problems and encouraging them to identify the different components of the problem, examine the relationships among these components, and consider the possible solutions.

U – Use of local context: Stresses the need to connect STEM education with learners' immediate environment, community experiences, local resources, and indigenous knowledge. Rather than presenting STEM concepts as abstract ideas that exist only in textbooks, learners can be encouraged to investigate sustainability challenges within their own communities and apply STEM knowledge to develop practical solutions. Research has linked indigenous science teaching to development of learners' cognitive reasoning, innovative thinking and critical thinking skills (Ayua et a., 2023c; Adam et al., 2024; Ayua et al., 2025).

S – Sustainable innovation: Encourages the use of STEM knowledge, creativity, design thinking, and engineering processes to develop innovative solutions to sustainability challenges. Rather than presenting STEM as a body of theoretical knowledge, this dimension encourages learners to apply what they learn to identify problems, generate ideas, design solutions, test prototypes, evaluate outcomes, and improve their designs. sustainable innovation positions learners not only as consumers of scientific and technological knowledge but also as potential innovators and problem-solvers. Design thinking provides an appropriate approach for promoting sustainable innovation because it encourages learners to understand the needs of people and communities before developing solutions. Incorporating green technology and engineering challenges into STEM education, students can develop the capacity to design solutions with less negative impacts on the environment. Innovative STEM teaching fosters and innovative skills in learners (Ayua et al., 2023)

T – Teacher capacity: Recognizes that the successful integration of sustainability into STEM education depends largely on teachers' knowledge, skills, attitudes, and confidence. Teachers require adequate preparation to connect STEM concepts with Education for Sustainable Development (ESD), facilitate interdisciplinary learning, and engage students in solving authentic sustainability problems. Teacher capacity development should equip

educators with practical skills for designing learner-centred and inquiry-based activities. Well-prepared teachers are better positioned to transform STEM classrooms into spaces where learners acquire knowledge, develop practical skills, and apply STEM to address real-world sustainability challenges.

A – Assessment for impact: Highlights the need to assess not only students' acquisition of STEM knowledge but also their ability to apply that knowledge to address real-world sustainability challenges. Traditional examinations often focus on students' ability to recall concepts, procedures, and facts, whereas sustainability-oriented STEM education requires learners to demonstrate how they can use knowledge to investigate problems, develop solutions, and evaluate their impacts. Assessment within the SUSTAIN-STEM Model should therefore include approaches such as project assessment, practical tasks, design challenges, presentations, problem-solving activities, and community-based projects. These approaches can provide evidence of learners' creativity, critical thinking, collaboration, innovation, systems thinking, and ability to apply STEM concepts to sustainability problems.

I – Inclusivity: Heartens equitable access to quality STEM and sustainability education for all learners irrespective of gender, location, socioeconomic background, or disabilities. Integrating inclusivity into sustainability-oriented STEM education requires deliberate efforts to remove barriers that limit learners' participation and achievement. Gender stereotypes, inadequate learning facilities, limited access to technology, poverty and geographical location can influence learners' opportunities to engage meaningfully in STEM. Inclusivity in SUSTAIN-STEM Model therefore promotes learning environments in which every learner is encouraged to participate, experiment, innovate, and contribute ideas to sustainability challenges.

N – Networking: Networking dimension emphasizes building partnerships and collaborative relationships among schools, universities, governments, industries, research institutions, communities,

NGOs, and international organizations to strengthen STEM education for sustainability. Global networking provides opportunities for sharing knowledge, technologies, teaching resources, research findings, and innovative practices across different contexts.

Thus, the SUSTAIN-STEM Model strengthens universal STEM education by promoting an approach to STEM teaching and learning that is inclusive, relevant, interdisciplinary, and connected to real-world sustainability challenges. Rather than treating Science, Technology, Engineering, and Mathematics as isolated subjects, the model connects STEM knowledge with issues such as climate change, energy, water, waste etc. This makes STEM education meaningful and encourages learners to apply their knowledge to problems within their communities and the wider world.

Educational Implications of the SUSTAIN-STEM Model

1. **Curriculum:** Shift from content acquisition to impact-driven, interdisciplinary learning embedding SDGs. Link outcomes to real-world problems like climate, energy, water and waste. Adopt **Green STEM** (*education that applies STEM to develop eco-friendly solutions for sustainability and climate changes*), **Eco-pedagogy** (*teaching approaches that use environmental issues and ecological values to help learners think critically and take action for sustainability*) and Project-Based Learning, plus **green laboratories** (*low-cost, environmentally sustainable laboratory spaces that uses recycled materials, renewable energy and eco-friendly practices to teach STEM through real-world sustainable problems*), **makerspaces** (*collaborative hands-on workshops where learners use materials, tools, and technology to design, build, test and share their creations*) and low-cost experiments using locally available materials. Move assessment from recall to assessment for impact — projects, design challenges, presentations and community-based tasks.
2. **Policy:** Government and stakeholders must provide sustainable funding for green

laboratories, digital resources and community projects, support continuous professional development in Education for Sustainable Development, reform assessment to value application over memorization, and strengthen Networking through partnerships among schools, universities, industries, NGOs and international organizations.

3. **Practice:** Build teacher capacity in systems thinking and constructivist, inquiry and design thinking pedagogies to facilitate learner-centred activities. Mainstream ESD and climate education in teacher training institutions. Ensure Inclusivity and Use of local context by linking indigenous knowledge to STEM, making learning equitable and culturally relevant regardless of gender, location or socio-economic background.

Potential Challenges to SUSTAIN-STEM model Implementation

1. **Resource constraints:** inadequate funding, poorly equipped laboratories, limited digital access, unreliable electricity and shortage of materials.
2. **Low awareness** among teachers and school leaders about STEM-sustainability connection.
3. **Exam-focused culture** that encourages memorization over creativity, critical thinking and innovation.

Combating Strategies

1. **Partnerships:** Governments, schools, industries, NGOs and communities pooling financial and technical resources.
2. **Open Educational Resources (OER):** Free textbooks, simulations, videos to reduce cost.
3. **Community projects:** Organizing learning around locally relevant issues — waste, water, energy, pollution; where learners collect data, design and test solutions, promoting systems thinking (York et al., 2019).
4. **International collaboration:** Joint research, virtual programs, teacher networks for sharing innovations and teaching resources, adapting global best practices to local contexts.

PILLAR 4: FOSTERING TRANSNATIONAL STEM EDUCATION UTILIZING CLIMATESMART PRACTICES

This pilar is presented as follows:

A. Is Climate Change a transnational STEM Education imperative? Why?

Yes, Climate Change is a transnational STEM Education imperative. Climate change is simultaneously a scientific, technological, engineering, mathematical, social and educational problem. Understanding temperature, rainfall, sea level and ecosystems requires scientific inquiry; developing renewable energy, climate-resilient infrastructure and water-management technologies requires engineering and technological innovation; and monitoring trends, modelling risk and evaluating interventions requires mathematics, statistics and computational methods. Therefore, it provides a natural setting for integrated STEM, not isolated concepts (Hakim et al., 2023; Tari et al., 2023). It is transnational because greenhouse-gas emissions, atmospheric processes, ocean systems, food systems, migration, water resources and technological transitions cross national boundaries. Climate problems are local and global. Thus, a flood in one location can be compared with flooding elsewhere using common STEM processes: collecting evidence, analysing local data, developing low-cost cooling or drainage interventions, and communicating findings internationally. According to Padhra and Tolouei (2023) and Ma and Chen (2023), climate education must be interdisciplinary, action-based and sensitive to Global South conditions, transforming scientific literacy into ability for change-making (Tasquier et al., 2022; Sezen-Barrie et al., 2025).

B. The CLIMATE-SMART Transnational STEM Framework

The CLIMATE-SMART Framework which involves Cross-border Collaboration, Localised context, Innovation, Measurement, Awareness, Teacher Capacity, Equity; links local realities to global knowledge networks via virtual laboratories and AI, making climate literacy a condition for sustainable development. The seven interdependent dimensions of the model are as shown in Figure 8.

Figure 8

The Climate-Smart Transnational STEM Framework



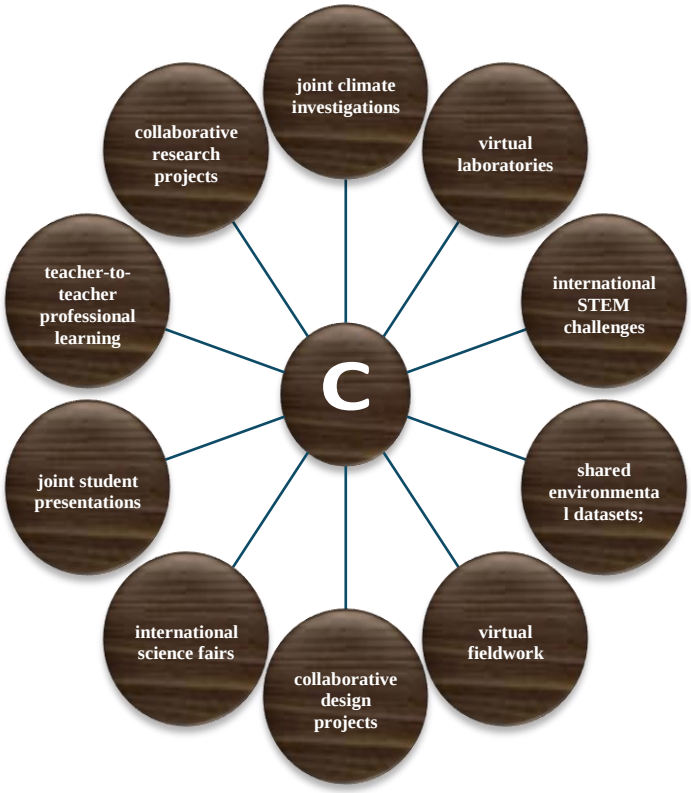
Figure 8 shows that the framework is not conceived as a linear activity in which one dimension is completed before another. However, the dimensions interact dynamically such that local climate problems stimulate investigation; investigation produces data; data support innovation; innovation requires collaboration; collaboration produces shared learning; and the whole process depends on teacher ability and equitable access.

C — Cross-border Collaboration

From Figure 8, cross-border collaboration is the defining of transnational component of the framework that learners and teachers could have structured opportunities to work with peers and institutions beyond their immediate geographical setting. Possible activities are presented in Figure 9.

Figure 9

C — Cross-border Collaboration



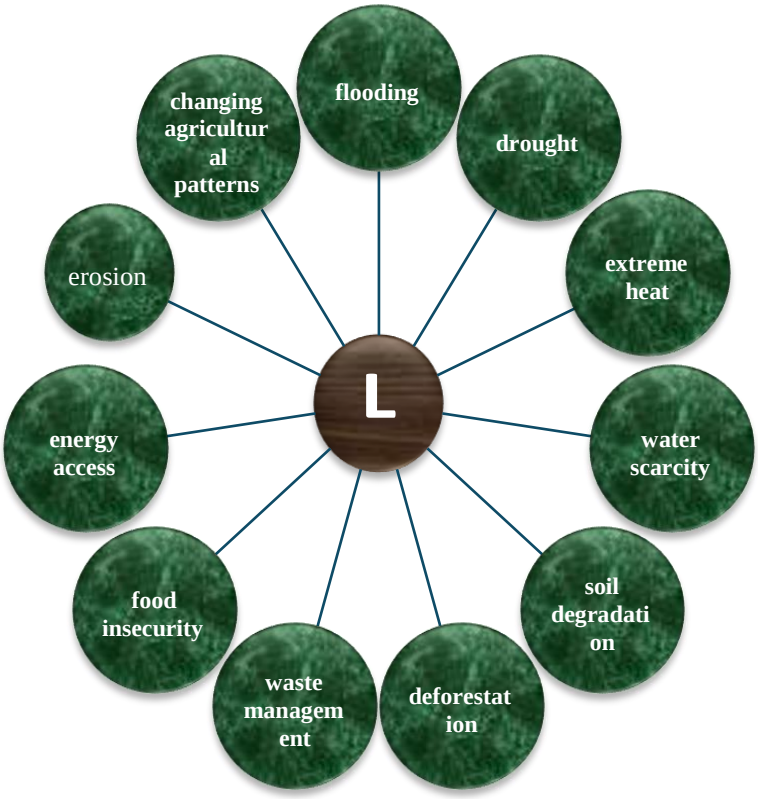
The Figure 9 shows that the goal is not international interaction for its own sake but collaboration may create educational value by allowing learners to compare environmental conditions, exchange interpretations and co-develop solutions. The advent of networks such as the Network for Emergent Socio-Scientific Thinking (NEST, 2024) reveals the potential of collaborative networks that work across borders, disciplines and generations to address complex environmental problems.

L — Localised Climate Context

Global climate education becomes meaningful when learners can connect it to problems they can observe. Localised climate setting is presented in Figure 10.

Figure 10

L — Localised Climate Context



As shown in Figure 10, the local setting can serve as the starting point for inquiry instead of the boundary of learning. For instance, a learner may examine flooding in Makurdi and subsequently compare rainfall, drainage and flood-management data with learners in another flood-prone region.

This has created a local-to-global learning architecture.

I —Innovation for Mitigation and Adaptation

The innovation dimension transforms STEM learning from problem recognition into solution-based development, the students may engage in activities as shown in Figure 11.

Figure 11

I —Innovation for Mitigation and Adaptation



Figure 11 reveal that innovation can be evaluated not only by technical novelty but also by feasibility, affordability, environmental sustainability, cultural appropriateness and potential social impact. The study on creative exploration is vital here because it divulge the value of learner-centred approaches for developing creative and practical competencies in science education (Terhemba & Ayua, 2025; Ayua et al., 2026e).

M — Measurement and Data

Climate-smart STEM education requires physical evidence; therefore, Students can be taught practically as presented in Figure 12.

Figure 12

M — Measurement and Data

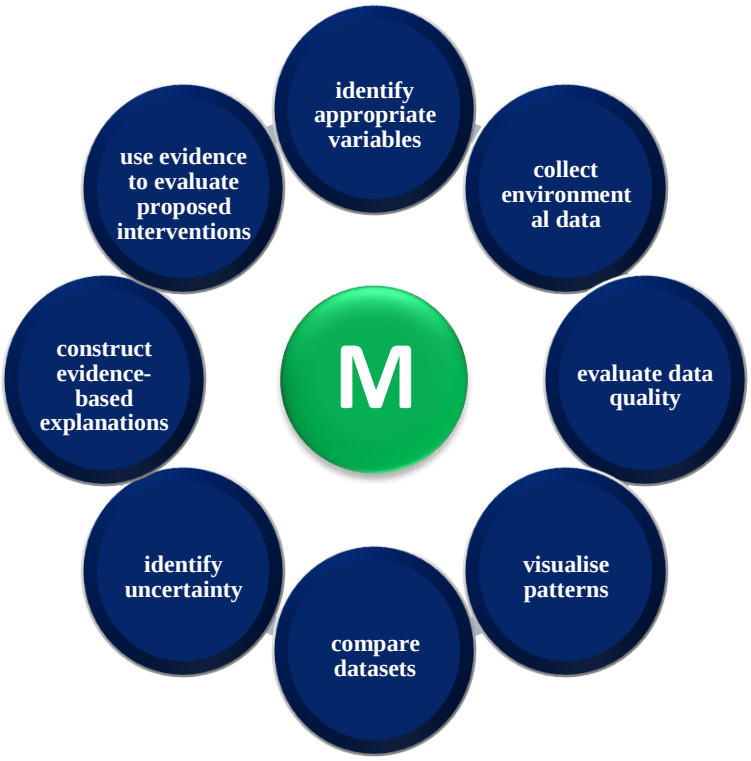


Figure 12 reveals that where infrastructure permits, students can use sensors, geographic information systems, remote sensing, Internet of Things (IoT) devices and computational tools. Artificial intelligence (AI) can support pattern recognition and data analysis, but students must learn to evaluate AI-generated outputs critically and thoughtfully. Climate learning suggest that data visualisation can make students' climate knowledge and motivation.

A — Awareness and Action

Climate education can connect knowledge with ethical action. Awareness requires understanding climate processes, risks and consequences; while action requires using this knowledge to make and evaluate decisions. The possible action-based project is presented in figure 13.

Figure 13

A — Awareness and Action

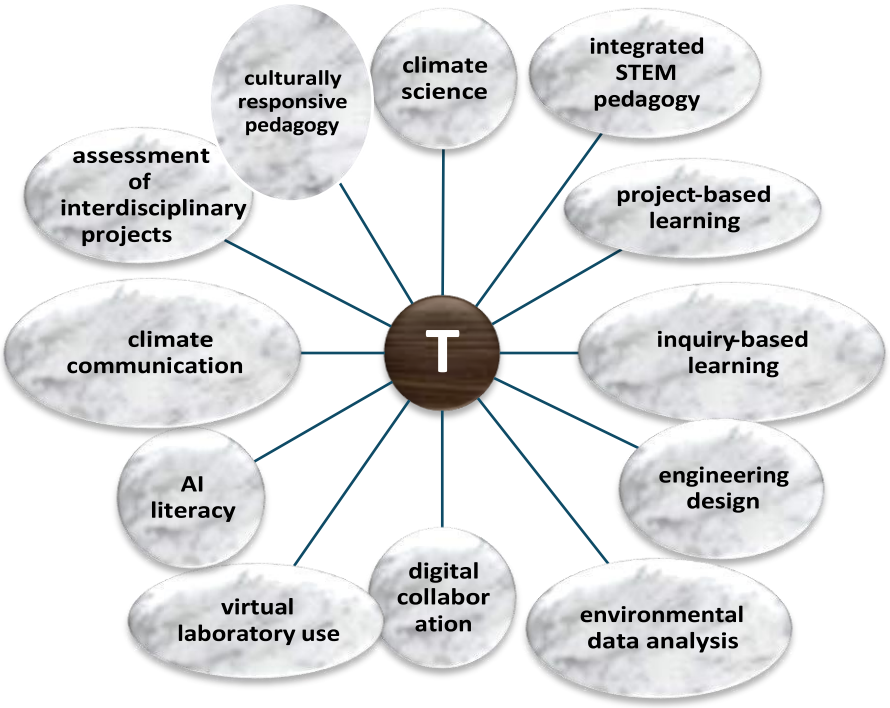


As present by Figure 13, it means that the emphasis can be on evidence-informed action rather than symbolic activities.

T — Teacher Capacity

Teachers are necessary because they are the core practice mechanism of this framework. Even cultured climate-STEM curricula may have limited effect if teachers lack content knowledge, technological competence, interdisciplinary pedagogical knowledge or confidence in teaching controversial and complex climate problems. This teacher development is therefore presented in Figure 14.

Figure 14
T — Teacher Capacity



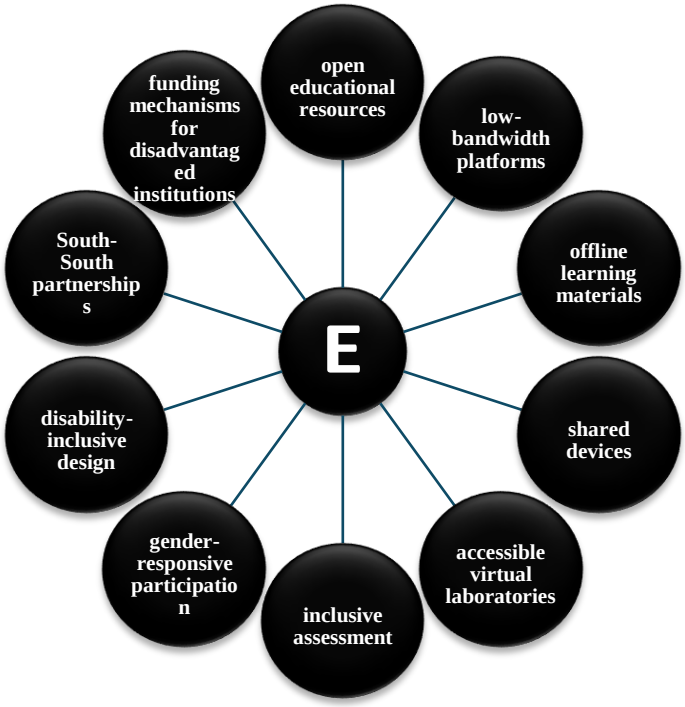
The Figure14 posits that the importance of teacher in this regard cannot be overemphasize, that is why Ibourk et al. (2025) show the importance of teacher climate-change knowledge and self-efficacy, while Rap and Blonder (2025) identify the role of technology acceptance in climate-change teaching.

E — Equity and Access

It is good to note that equity is not an additional component of climate-smart STEM education but it is a condition for its legitimacy. Transnational STEM programmes can by mistake reproduce educational inequalities if participation depends on high-speed internet, expensive devices, international travel or well-resourced institutions, therefore equity is shown in Figure 15.

Figure 15

E — Equity and Access



This dimension presented in Figure 15 is vital for African and other Global South settings, where digital and infrastructural differences can hinder participation in international education networks. Also, there are studies that shows the importance of digital inclusion and gender equity in STEM participation, including the potential and risks associated with AI-supported digital education (Ayua et al., 2026b; Terhemba & Ayua, 2026).

Educational Implications of the CLIMATE-SMART STEM Framework

1. **Curriculum:** Shifts climate change from isolated environmental topic to climate-infused STEM. Learning is organized around authentic problems — learners examine local temperature, rainfall and flood data, develop low-cost mitigation/adaptation interventions (Ayua et al., 2026e), calculate energy use and communicate findings internationally. Assessment moves from exams to portfolios, prototypes, data analyses and collaborative products.
2. **Teacher Education:** Requires building teacher climate knowledge, self-efficacy, interdisciplinary pedagogy and technology acceptance. Teachers become core mechanism, needing professional learning communities, co-design of climate projects, and competence in virtual laboratories and AI literacy with scientific integrity.
3. **Policy & Equity:** Governments must invest in digital infrastructure, electricity and laboratories, identify climate as a cross-curricular STEM priority, and support reciprocal, low bandwidth and offline international partnerships that position Global South learners as knowledge producers, not passive recipients.

Constraints to Implementation

1. Unequal access to broadband, electricity, digital devices and technical support, especially in developing countries.
2. Subject-siloed national curricula and examination pressure limiting interdisciplinary climate STEM projects.
3. Teachers lacking climate knowledge, interdisciplinary pedagogy and digital competencies; low technology acceptance.
4. High cost of coordination, equipment, translation, connectivity and data management for transnational projects.
5. Language, cultural and educational tradition differences; traditional exams fail to capture collaboration, design thinking and climate action.

Combating Strategies

1. Develop openly licensed, adaptable low-cost climate-STEM resources supporting asynchronous and offline participation.
2. Build reciprocal partnerships across the globe, plus school-university-agency collaboration.
3. Establish professional learning communities for co-designing projects and training teachers.
4. Integrate responsible AI and virtual laboratories, and reform assessment to portfolios, prototypes and collaborative products.

CONCLUSION

The future of STEM education cannot be memorized! It must be imagined, engineered and sustained. This paper shows that when Creativity ignites inquiry, AI personalizes learning, Sustainability ground purpose, and Climate-Smart practices connect local action to global impact, and STEM education becomes transformative.

RECOMMENDATIONS

Based on the synthesis of the four frameworks, the following recommendations are made:

1. **Curriculum and Pedagogy Redesign:** There should be a shift from rote content transmission to impact-driven and interdisciplinary STEM education that embeds curiosity-driven inquiry and design thinking.
2. **Ethical and Human-Centred AI Adoption:** Educational institutions should adopt Artificial Intelligence to augment and support teachers through adaptive learning, intelligent tutoring and smart assessment, rather than replace them.
3. **Localization of STEM Learning:** STEM curricula should be localized to solve real-world sustainability and climate challenges within local contexts while promoting cross-border collaboration and knowledge sharing.
4. **Democratization of STEM Infrastructure:** Governments, institutions and development partners should promote equity through low-cost laboratories, open educational resources (OER) and South-South collaboration among developing countries.
5. **Institutional Investment and Policy Reform:** Stakeholders should redesign curricula, empower teacher training institutions to produce sustainability and climate-literate STEM teachers, fund green laboratories and makerspaces, and establish reciprocal intercontinental partnerships for sustainable development.

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