



Fostering Transnational Science, Technology, Engineering and Mathematics Education: An Exploration of Climate-Smart Practices

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Abstract

This paper discusses the pressing need for a transboundary approach to tackle climate change through STEM education, which is currently limited by traditional education methods. It introduces the Climate-Smart Transnational STEM Framework, encompassing seven dimensions: Cross-border Collaboration, Localised Climate Context, Innovation for Mitigation and Adaptation, Measurement and Data, Awareness and Action, Teacher Capacity, and Equity and Access. Grounded in theories like Connectivism and Education for Sustainable Development, the framework aims to connect local climate issues with global knowledge networks, promoting a collaborative learning approach. It addresses challenges specific to Africa and the Global South, such as infrastructural inequalities and digital exclusion, while offering a conceptual model for curriculum designers and educators to align STEM education with Sustainable Development Goals. Future studies are called for to validate the framework across diverse educational and climate contexts.

Keywords: climate-smart education; STEM education; transnational education; climate literacy; systems thinking; digital learning; Global South

Introduction

Education is supposed to make learners not just for involvement in existing social and economic systems but for responding critically and creatively to complex and fast ever-evolving global conditions. Now, education requires knowledge, skills, dispositions and capacities that enable learners to examine problems, evaluate evidence, collaborate with others and develop novel and



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practical solutions. Regarding science education, these expectations are vital due to the problems like climate change, biodiversity loss, food insecurity, energy transitions, environmental degradation and technological disruption cannot be effectively addressed through lonely disciplinary knowledge. Ayua et al. (2026d) stresses the relevance of critical, creative, practical and solution-based science education for sustainable development, including the development of learners' creative minds and hands. The STEM education is needful for such relevance through creative exploration as confirmed by Ayua et al. (2026d); Ayua et al. (2026f); Terhemba and Ayua, (2025) that this can show the potential of learner-centred science experiences for strengthening creative thinking and practical competencies. Science, Technology, Engineering and Mathematics (STEM) education pave way for proper educational platform for solving these problems because it brings together scientific inquiry, technological applications, engineering design and mathematical reasoning. Unified STEM education can create opportunities for learners to investigate authentic problems instead of treating scientific and mathematical knowledge as disconnected bodies of content. Joined STEM educational approaches can support students' creativity, engagement, critical thinking, problem-solving and application of knowledge to real-world situations (Anwar, 2022; Han et al., 2022; McLure et al., 2022). The advancement of sustainability agenda further makes stronger the case for connecting STEM education with environmental and climate-related problems. Climate change creates an important framework for this integration. This requires physical and biological processes which need scientific understanding; technologies for observation, communication, classification and mitigation; engineering solutions for resilience, infrastructure and renewable energy; and mathematical process for analysing trends, risks and environmental data.

Climate change is basically transnational since greenhouse-gas emissions, atmospheric processes, ocean systems, food systems, migration, water resources and technological transitions cross national boundaries. Educational responses could enable learners to understand both the local manifestations and global interconnectedness of climate change. There can be climate education that is interdisciplinary, action-based and connected to learners' live experiences. According to Padhra and Tolouei (2023) climate-change education can be embedded across higher-education programmes instead of limiting it to specialised courses. Moreso, Ma and Chen (2023) show the problems of climate-change education in the Global South, where educational responses must be sensitive to local environmental, economic and institutional conditions. Climate education can become a powerful framework for developing STEM competencies while making stronger learners' climate literacy and skilful for action. Despite this potential, STEM education is still uneven. The disciplines may be taught separately, climate issues may be presented as general environmental topics instead of STEM design problems, and chances for students to collaborate internationally may remain limited. McLure et al. (2022) reveal that integrated STEM projects make authentic problem-solving opportunities, but practice is still dependent on teacher capacity, curriculum structures, resources and institutional support. At the same time, dissimilarities in connectivity, devices, laboratories, teacher readiness and teacher preparation and funding may prevent learners in lower-resource situations from participating meaningfully in digitally mediated international STEM experiences.

This paper addresses the yawning gap by presenting a framework that integrate STEM, climate-smart practice and transnational collaboration. It builds on the creative science learning, practical competencies, digital education and inclusive STEM participation (Ayua et al., 2026e). Studies address creative exploration, AI-supported learning, digital classrooms, gender and STEM participation, and inclusive science education (Ayua et al., 2026a; Terhemba et al., 2025; Terhemba



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& Ayua, 2025). These strands create a useful basis for covering the discussion from locally situated innovative science teaching to globally connected, climate-oriented STEM education. The focus of this paper is that climate-smart STEM education can connect local environmental realities to global knowledge networks. However, how can climate-smart practices be intentionally organised within STEM education to promote cross-border collaboration, climate literacy, innovation, teacher capacity and educational equity?

Climate Change as a Transnational STEM Challenge

Climate change is a scientific, technological, engineering, mathematical, social and educational problem. Comprehending fluctuations in temperature, rainfall, sea level, atmospheric composition and ecosystem dynamics needs scientific inquiry and interpretation of empirical evidence. Making available and sustaining renewable-energy systems, climate-resilient infrastructure, water-management technologies and adaptation technologies needs engineering and technological innovation. Also, monitoring trends, modelling risk and evaluating interventions need mathematics, statistics and computational methods. Therefore, climate change creates a natural setting for integrated STEM learning instead of teaching students isolated concepts such as energy, heat transfer, measurement, statistics or environmental science, teachers can organise learning around reliable problems. Students, for instance, may examine how rising temperatures can affect their community, analyse local temperature data, develop a low-cost cooling intervention, calculate energy requirements and communicate their findings to students in another country experiencing a different climate problem. Researches show developed STEM-based learning materials around global warming and reported improvements in students' STEM literacy and the STEM-based physics teaching materials addressing climate change improved high-school students' climate literacy (Hakim et al., 2023; Tari et al., 2023). This means that engagement with climate-related data and visualisations can improve climate knowledge and situated interest among secondary students. The relevance of climate education is beyond knowledge acquisition, therefore, scientific literacy for climate action necessitates learners to interpret evidence, identify uncertainty, evaluate competing claims, consider ethical implications and participate in up-to-date decision-making. That is why Tasquier et al. (2022) and Sezen-Barrie et al. (2025) conceptualise scientific literacy as ability for change-making in relation to complex societal problems like climate change and that climate and environmental education requires transformational approaches that connect scientific comprehension with action, justice and learners' lived realities.

From Disciplinary STEM to Integrated and Sustainability-Based STEM

Integrated STEM (iSTEM) education is an approach that connect disciplines around meaningful problems instead of just placing Science, Technology, Engineering and Mathematics beside one another. The division is vital, however, teaching four STEM subjects within the same institution does not really produce integrated learning. Integration of STEM education requires learners to mobilise knowledge from various domains to explore, design, test, evaluate and communicate solutions. According to McLure et al. (2022) school-based iSTEM education projects generally involve authentic problems, interdisciplinary knowledge and design-oriented learning and Han et al. (2022) also confirms that sustained integrated STEM practice can be continued only when teachers develop shared practices and institutional support. Furthermore, positive learning outcomes associated with an iSTEM curriculum is usually united in middle-school life science (Anwar, 2022). The continuity programme may create an additional rationale for integration. Addressing environmental problems, STEM education can become a mechanism instead of just preparing students for examination-based STEM careers. There is need and interest in integrating Education for Sustainable Development with

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STEM education (Habibaturrohman et al., 2023) and there is evidence on STEM-based teaching and the Sustainable Development Goals that STEM can contribute to critical thinking, creativity, innovation and problem-solving relevant to sustainable development. The conceptual framework is therefore presented in Figure 1.

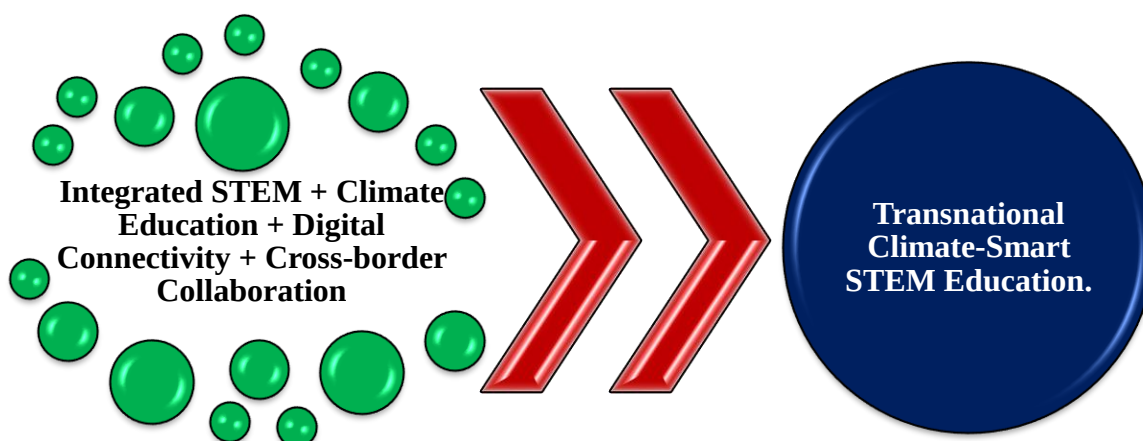


Figure 1: Conceptual Framework

This formulation in Figure 1, moves the discussion beyond conventional integrated STEM by adding two dimensions that is usually treated separately: climate action and transnational learning.

Climate-Smart Education and Climate Literacy

Climate-smart education as shown in Figure 1 simplifies the educational practices that enable learners to understand climate procedures, explore climate-related risks, develop mitigation and adaptation solutions, use evidence and technology responsibly, and participate in individual and collective climate action. Climate literacy can be more than just knowing that climate change is taking place. It involves comprehending climate systems, interpreting evidence, identifying human and environmental consequences, evaluating solutions and developing the ability to make well-versed decisions. Climate literacy can be made stronger through appropriately designed STEM learning as shown the connection in Figure 1. STEM-based physics teaching materials improved climate literacy among high-school students and low-cost Do It Yourself (DIY) model kits could improve conceptual understanding of climate change among preservice teachers (Srichaitung, et al., 2025 & Hakim et al., 2023). In this regard teachers' ability is very vital as Ibourk et al. (2025) examined teachers' climate-change knowledge and self-efficacy and highlighted the importance of learning technologies in supporting teachers' ability to teach climate change. More to this, Rap and Blonder (2025) investigated technology acceptance in climate-change teaching and reveals that teachers' perceptions use of technology can influence how digital tools are amalgamated into climate-related teaching. That is to say that, climate-smart STEM education can address two correlated abilities including learner climate literacy and teacher climate-pedagogical ability.

Transnational STEM Education

As presented in Figure 1, Transnational STEM Education (T-STEM-E) simply has to do with learning, teaching, researching and curriculum activities that connect learners, educators, researchers or institutions across national boundaries around STEM-related knowledge and problems. As shown in Figure 1, it may involve virtual classrooms, joint projects, international competitions, shared datasets, collaborative research, student mobility, joint curriculum development, virtual laboratories

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and co-designed problem-solving activities. The transnational dimension presented in Figure 1 is vital to climate change because climate problems are simultaneously local and global. For instance, a flood-prone Nigerian community may examine rainfall patterns and drainage systems while collaborating with learners in another country investigating flooding, coastal erosion or water management. The two groups may encounter different environmental conditions but use common STEM processes to collect evidence, analyse data and develop solutions. Digital technologies presented in Figure 1 can make such collaboration feasible. Learners can have access to experimentation when physical facilities are unavailable or geographically inaccessible through Virtual laboratories. Physical and virtual investigations can support conceptual knowledge acquisition (Mulwijk & Lazonder, 2023). Furthermore, Flegr et al. (2023) reveals the educational value of combining virtual and video-based experiments in remote STEM learning and May et al. (2023) further conceptualised online laboratories as sociotechnical-pedagogical environments requiring link among technology, pedagogy and institutional conditions. Transnational learning cannot be reduced to technological connectivity, however, for effective collaboration, it requires shared objectives, culturally responsive pedagogy, equitable participation, teacher coordination, data governance, appropriate assessment and institutional commitment.

Theoretical Foundation

Theoretically, this paper was anchored on theoretical framework presented in Figure 2.

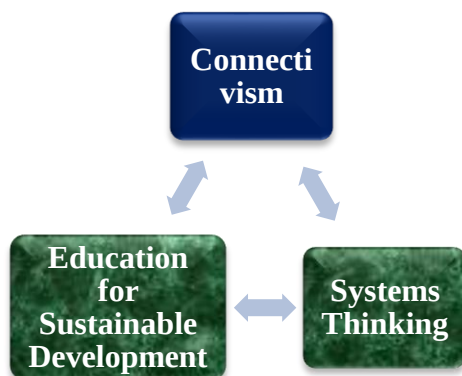


Figure 2: Theoretical Framework

Siemens' (2005) Theory of Connectivism as presented in Figure 1 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. 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 2, Education for Sustainable Development (ESD) highlights knowledge, competencies, values and action for solving social, environmental and economic problems. Its importance to this framework

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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 (Habibaturrohman 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 2 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 2 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.

The CLIMATE-SMART Transnational STEM Framework

This paper presents **Climate-Smart Transnational STEM Framework**, comprising seven interdependent dimensions as shown in Figure 3.

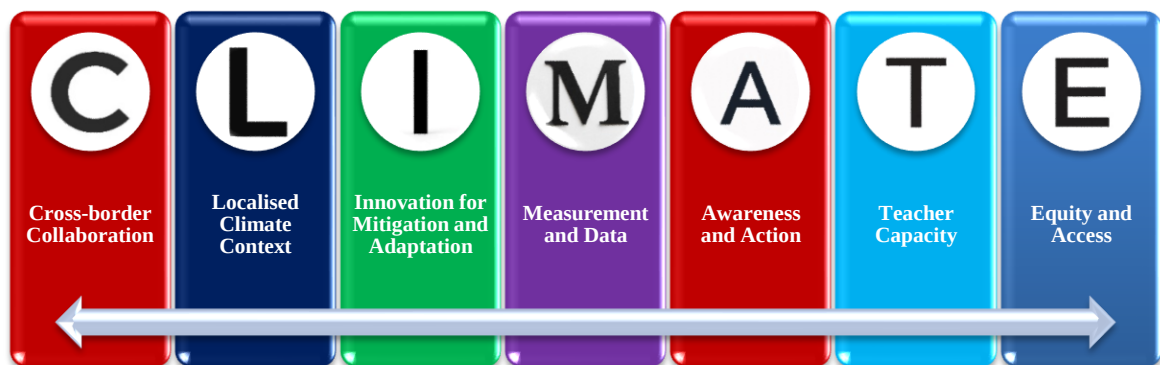


Figure 3: The Climate-Smart Transnational STEM Framework

Figure 3 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 3, 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 4.

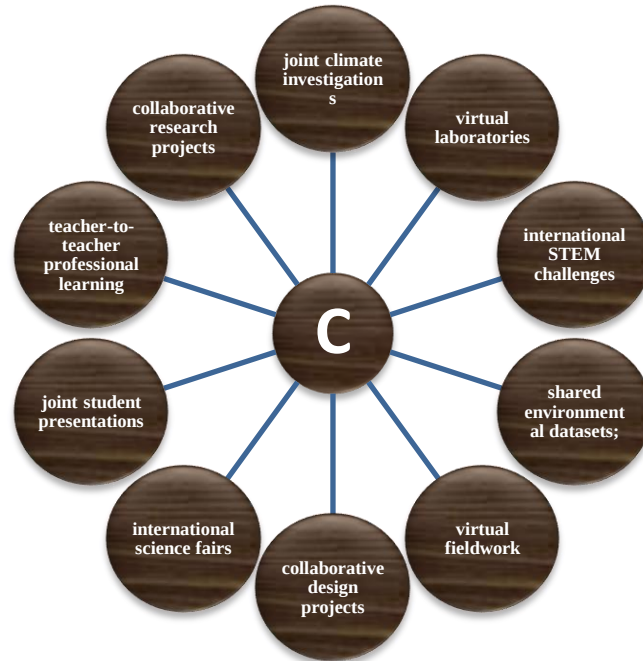


Figure 4: C — Cross-border Collaboration

The Figure 4 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 5.

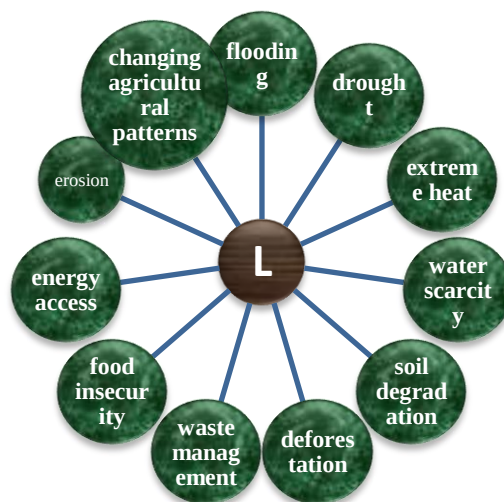


Figure 5: L — Localised Climate Context

As shown in Figure 5, 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

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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 6.



Figure 5: **I —Innovation for Mitigation and Adaptation**

Figure 5 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 6.

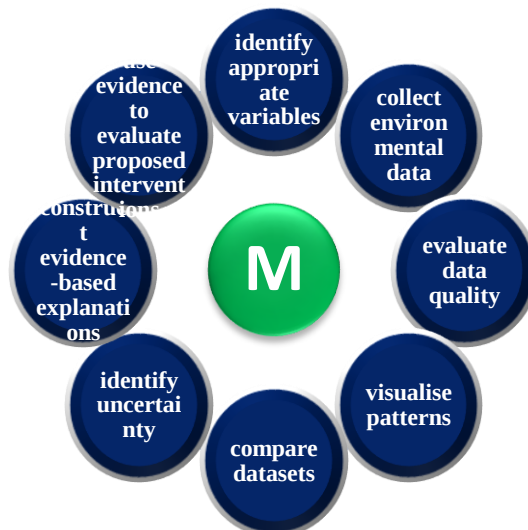


Figure 6: M — Measurement and Data

Figure 6 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 projects is presented in figure 7.



Figure 6: A — Awareness and Action

As present by Figure 6, it means that the emphasis can be on evidence-informed action rather than symbolic activities.

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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 8.

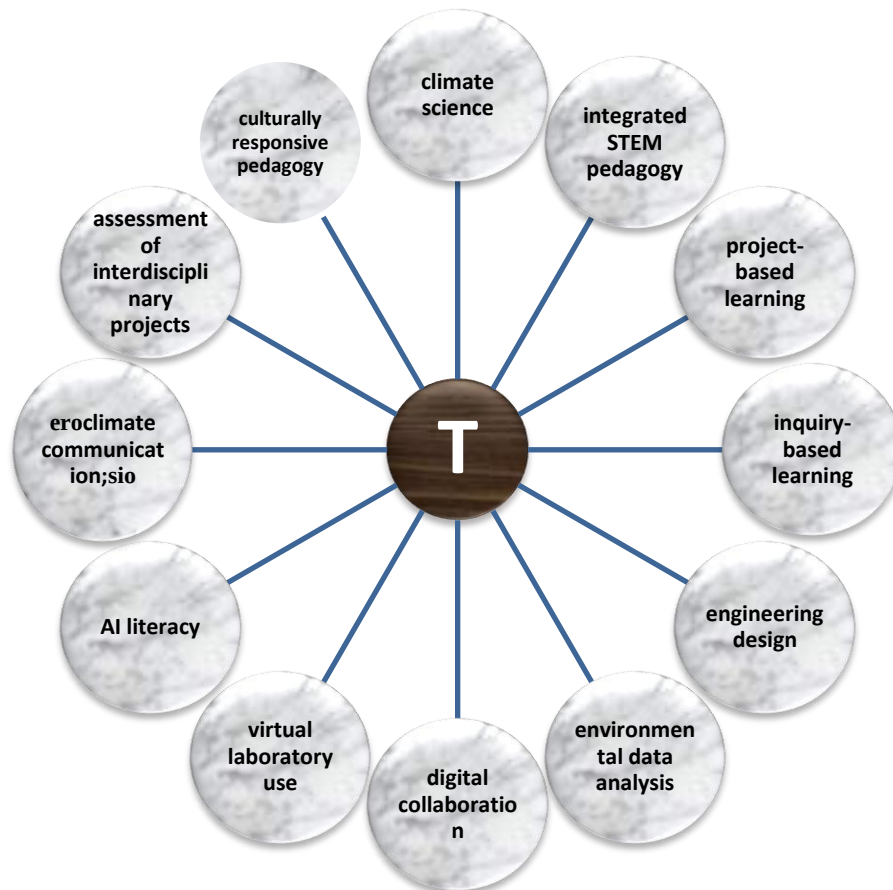


Figure 8: T — Teacher Capacity

The Figure 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 9.

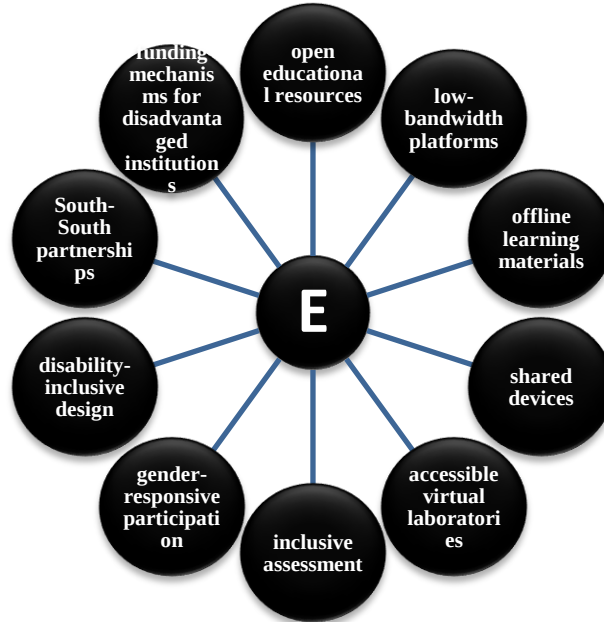


Figure 9: **E — Equity and Access**

This dimension present in Figure 1 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).

Operational Pathway of the Framework

The seven dimensions can be operationalised through learning cycle as shown in Figure 10.



Figure 10: Operational Pathway of the Framework



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This operational pathway of the framework in Figure 10 shown in cycle distinguishes the Climate-Smart Transnational STEM Framework from conventional climate-awareness programmes. Here, the learner is not just positioned as a recipient of climate information but as an investigator, designer, collaborator and potential change-maker.

Virtual Laboratories and Digital Platforms

Digital technologies can cover transnational STEM education beyond visible mobility. Virtual laboratories can direct learners to conduct simulations, analyse experimental data and explore phenomena that may be difficult or expensive to investigate physically. According to Mulwijk and Lazonder (2023) both physical and virtual investigations can backup to conceptual knowledge acquisition. The usefulness of virtual and video experiments for STEM learning when conventional laboratory access is constrained and the successful online laboratories depend on the interaction between technological, pedagogical and institutional factors (Flegr et al., 2023 & May et al., 2023). Regarding the Climate-Smart Transnational STEM Framework, virtual laboratories can complement instead of automatically replacing physical experiences. In situations where physical facilities are available, blended laboratory models may provide the strongest opportunities for connecting observation, simulation and real-world measurement.

Artificial Intelligence (AI), Data and Climate-Smart STEM

AI presents extra potentials for climate-smart STEM education, it can assist learners in organising large datasets, identifying patterns, generating simulations, supporting coding and exploring alternative scenarios. It can facilitate communication among learners participating in transnational projects. Nevertheless, AI could be merged within a framework of scientific integrity and critical evaluation. It is needful for students to understand that AI-generated information may contain errors, biases or unsupported claims. studies highlight perceived benefits for research self-efficacy and attitudes, while their work on scientific integrity stresses the ethical challenges created by generative AI in science education research (Ayua et al., 2026c). Climate-smart AI education may add: AI literacy; source verification; data provenance; transparency of AI use; privacy protection; responsible data sharing; bias awareness; and academic and scientific integrity. AI can function as an augmentation tool, not as a substitute for scientific reasoning.

Africa and the Global South: Contextualising Transnational STEM

The Global South shows both challenges and vital opportunities for climate-smart STEM education. Communities in Africa are experiencing climate-related problems while simultaneously confronting infrastructural and educational disparities. A globally designed STEM programme may fail if it assumes that all schools have equivalent connectivity, laboratories, electricity, devices and teacher expertise. Transnational STEM education must therefore avoid a one-directional model in which knowledge flows from highly resourced institutions to less-resourced institutions. Instead, the Climate-Smart Transnational STEM Framework advocates reciprocal knowledge exchange. Students in Nigeria for instance may contribute knowledge concerning flood management, agricultural adaptation or local ecological practices, while international partners contribute alternative technologies, datasets or analytical tools. Such collaboration positions African learners as knowledge producers instead of passive recipients. This principle is consistent on the challenges of climate education in the Global South and with scholarship advocating for more inclusive and transformative approaches to climate education (Ma & Chen, 2023).

Major Barriers to Implementation

The major barriers or hindrances for practice is highlighted in Figure 12.



Figure 12: Barriers to Implementation

Figure 12 presented that the unequal access to broadband internet, electricity, digital devices and technical support can limit participation. National curricula may be planned by individual subjects and examination requirements, making interdisciplinary climate-STEM projects difficult to practice. Teachers may lack the climate knowledge, interdisciplinary pedagogical knowledge and digital competencies required. International projects actually need resources for connectivity, teacher training, equipment, coordination, translation, travel and data management. Transnational learning can be affected by changes in language, cultural expectations, educational traditions and communication practices. Traditional examinations may not adequately capture collaboration, design thinking, climate action, data literacy or interdisciplinary problem-solving. Short-term projects may produce enthusiasm without establishing institutional structures that sustain collaboration.

Strategies for Implementation

Here are the following strategies that can strengthen practice as presented in Figure 13.



Figure 14: Strategies for Practice

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Figure 14 present that climate-STEM teaching resources can be openly licensed and adaptable to different settings. Institutions in many areas of Africa, Asia, Latin America and other Global South regions can develop reciprocal STEM-climate partnerships based on shared problems. Platforms can support asynchronous communication, downloadable resources and offline participation. Teachers from participating countries can form professional learning communities to co-design climate-STEM projects and share classroom experiences. Schools, colleges, universities, research organisations, environmental agencies and technology organisations may collaborate on long-term programmes. AI tools could be integrated with explicit instruction in scientific integrity, verification, privacy and responsible use. Assessment may include portfolios, design prototypes, research reports, data analyses, presentations, collaborative products and reflective accounts.

Implications for Curriculum Development

Curriculum developers may move from climate content being treated as an isolated environmental topic towards climate-infused STEM curricula as the example is shown in Figure 15.

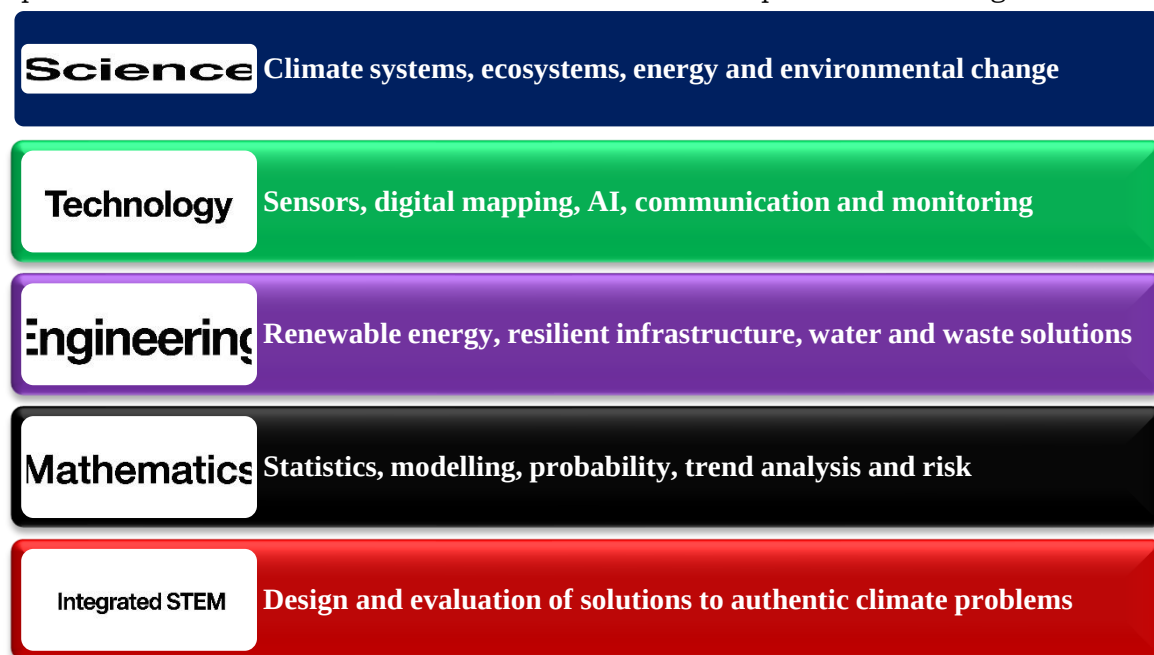
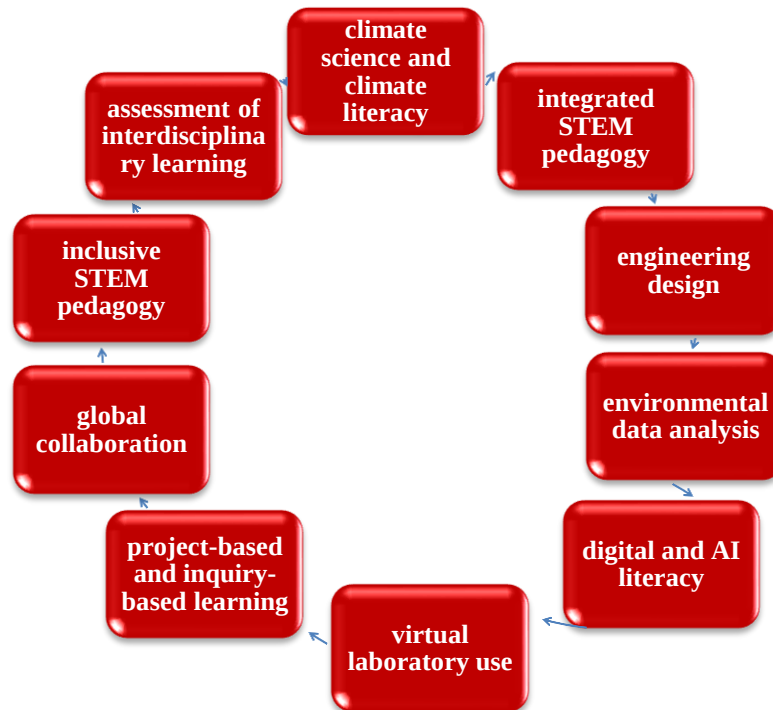


Figure 15: Implications for Curriculum Development

Figure 15 shows that such curriculum integration can increase the relevance of STEM education while supporting sustainability competencies.

Implications for Colleges of Education and Teacher Education

The Colleges of Education and teacher education have a vital role to play because they prepare teachers who can practice STEM and climate education in schools. Teacher education curricula can incorporate the following as presented in Figure 16.



Figurer 15: Implications for Colleges of Education and Teacher Education

Figure 15 present that teacher candidates can participate in international virtual projects where possible. Such experiences can help them develop confidence in collaborating with educators and learners from different settings.

Policy Implications

The framework has several policy implications: national education policies could identify climate change as a cross-curricular STEM priority instead of confining it to environmental education. Governments can invest in digital infrastructure, electricity, laboratories and teacher professional development. International organisations may support equitable transnational STEM programmes that do not exclude low-resource schools. Policymakers can create mechanisms for identification of learning achieved through international virtual projects and collaborative STEM programmes. Funding mechanisms could prioritise partnerships that show reciprocal participation instead of one-way knowledge transfer.

Scholarly Contribution of the CLIMATE-SMART Framework

The input of this paper lies in integrating three areas that are often discussed separately: climate-smart education, integrated STEM education and transnational learning. Existing integrated STEM literature makes evidence that interdisciplinary STEM projects can support authentic problem-solving and student learning (McLure et al., 2022; Han et al., 2022). According to Padhra and Tolouei, (2023); Sezen-Barrie et al. (2025) posits that there is need for scientific literacy, action and contextualisation. Digital learning scholarship also shows the potential of virtual experimentation and technology-mediated learning (Mulwijk & Lazonder, 2023; Flegr et al., 2023). The framework joins these strands through a single educational architecture presented in Figure 17.

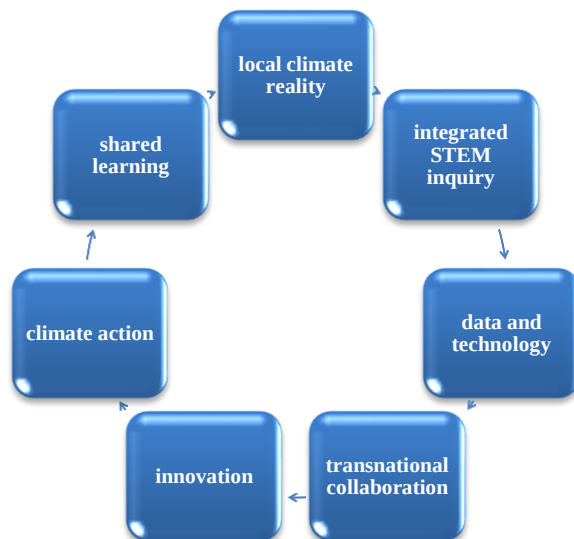


Figure 17: Educational Architecture for the Framework

The Figure 17 reveals that this provides a conceptual basis for moving from integrated STEM to climate-smart transnational STEM.

Proposed Research Agenda

Instead of being seen as an established intervention paradigm, the framework can be empirically validated. Future research can look into the following: Do students who engage in Climate-Smart projects show higher levels of STEM achievement and climate literacy than students who get traditional instruction? How well does the framework work in nations with various educational systems and climatic risks? Which professional development programs best equip educators for international STEM that is climate-smart? What effects do offline and low-bandwidth methods have on students' participation in underprivileged communities? Does the framework increase girls' and students with disabilities' meaningful involvement in STEM? Do climate-smart STEM experiences lead to long-term environmental activity, STEM identity, and climate knowledge? How might AI aid in the study of climate data while upholding learner autonomy and scientific integrity?

Conclusion

We need education responses to climate change that are scientifically sound, technologically capable, locally relevant and globally connected. STEM education offers a powerful platform for developing the knowledge and competencies necessary to investigate climate problems, analyse evidence and design mitigation and adaptation solutions. Yet, the full capacity of STEM for climate action cannot be realised when STEM disciplines are still isolated, climate education is still informational, or learning is still confined within national and institutional boundaries. This paper presents the Climate-Smart Transnational STEM Framework, comprising Cross-border Collaboration, Localised Climate Context, Innovation for Mitigation and Adaptation, Measurement and Data, Awareness and Action, Teacher Capacity, and Equity and Access. The framework uses local climate challenges as entry points for STEM inquiry, and utilises digital networks to connect learners across geographical boundaries. Transnational education should not be an additional mechanism for already advantaged institutions to accumulate international opportunities. Rather, it can enable a reciprocal sharing of knowledge in which institutions and learners in Africa and other contexts of the Global South can add their own environmental knowledge, innovations and experiences. The paper conceptually



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advocates for a transition from local STEM education to globally connected, climate-smart STEM education. Such a transition can feed into the ambitions of SDG 4 through stronger inclusive and relevant quality education and SDG 13 through the development of climate literacy, adaptation capacity and informed action. The framework is a proposition that needs empirical testing. Its value may ultimately depend on whether further research shows that climate-smart transnational STEM learning can enhance learners' STEM competencies, climate literacy, creativity, collaboration, data literacy, equity of participation and ability for meaningful climate action.

Recommendations

The following recommendations were made that:

1. Governments and education authorities should develop fundable climate-smart STEM programs that integrate teacher professional development, digital infrastructure, environmental data resources, laboratories, and transnational school partnerships, with a focus on underserved communities.
2. Professional-learning networks and open, culturally sensitive climate-STEM materials be established by teacher-education institutions and international education organisations. These programs will assist educators in creating cross-border learning opportunities, virtual labs, multidisciplinary projects, and climate-data research.
3. By creating climate/STEM laboratories, forming reciprocal international partnerships, integrating regional climate issues into STEM curricula, and assessing students using real project-based evaluation, schools, colleges, and universities should institutionalise climate-smart transnational STEM projects.

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