



Strengthening Mathematics and Science

Education in Africa

[SMASE-AFRICA]

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[Secretariat]

National Science Centre (NSC)

Ministry of Education

Private Bag 5, Woodlands, Lusaka,
Zambia

Tel +260-211-262391 or +260-211-
266772

Email: jstemea@gmail.com

Contact Information

[Regional Secretariat]

Strengthening Mathematics and Science Education in Africa (SMASE-Africa) P. O. Box 22949-
00505

Located inside the University of Nairobi - Kenya Science Campus, Ngong Road Nairobi,
Kenya.

Tel: +254 720 073 533

E-mail: info@smase-africa.org

Website: www.smase-africa.org



**Journal for Science, Technology, Engineering and Mathematics Education in
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Strengthening Mathematics and Science Education in Africa

SMASE-AFRICA



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Preface

Welcome to Volume 1, Number 1, January 2026 Edition of the Journal for Science, Technology, Engineering and Mathematics Education in Africa (JSTEMEA)

The 22nd Conference on Mathematics, Science and Technology Education in Africa (COMSTEDA 22), held from 12th – 14th November 2025 at the Bingu International Conference Centre in Lilongwe, Malawi, brought together educators, policymakers, researchers, industry experts, and development partners from across the continent. Guided by the theme, “Reimagining STEM for a Pan-African Future: Bridging Education, Innovation, and Sustainable Development Towards Agenda 2063”, the forum reaffirmed the collective African commitment to reimagining STEM education in ways that equip learners with knowledge, skills, values, and attitudes relevant for 21st century living.

This edition of the journal captures a selection of fifteen (15) peer-reviewed papers presented at the conference. These papers reflect the conference sub-themes, namely:

- 1. Decolonizing STEM Curricula: Centering African Knowledge Systems and Sustainable Practices**
- 2. Pan-African Innovation Hubs: Leveraging Technology and Entrepreneurship for Inclusive Growth**
- 3. Gender Equity in STEM: Empowering Women and Girls as Leaders of Africa’s Sustainable Future**
- 4. STEM for Climate Resilience: Adaptive Solutions for a Changing Africa**
- 5. Policy Harmonization and Cross-Border Collaboration for a Unified STEM Agenda**

Together, these contributions showcase both theoretical perspectives and classroom-based practices, enriching the ongoing dialogue on STEM education in Africa. They also highlight practical innovations ranging from the integration of indigenous resources and preventive maintenance into STEM learning to low-cost engineering and robotics, project-based learning and formative, competence-based assessment that mirror the dynamism of education systems across the continent.

Acknowledgements

We extend our deepest appreciation to the Government of the Republic of Malawi and the Ministry of Education, Malawi, for graciously hosting COMSTEDA 22 at the Bingu International Conference Centre in Lilongwe in partnership with SMASE-Africa.

We are equally indebted to the organizing committees, keynote speakers, and session chairs whose tireless efforts ensured a vibrant and engaging forum. Our thanks also go to SMASE-Africa partners, whose material, financial, and technical contributions enriched the conference. Finally, to all delegates, paper presenters, and participants onsite and online. We are grateful for your commitment, insights, and dedication to advancing STEM education in Africa.

Looking Ahead

As SMASE-Africa continues to serve as a continental hub for strengthening STEM education, this journal is more than a record of proceedings. It is a springboard for further inquiry and innovation. We hope that readers will find in these pages not only valuable research but also practical insights to inspire reforms in classrooms, policies, and institutions across Africa.

We look forward to building on the momentum of Lilongwe as we prepare for COMSTEDA 23, confident that each forum brings us closer to realizing the African Union's Agenda 2063 and the aspirations of SDG 4: Quality Education.

About SMASE-Africa and COMSTEDA

SMASE-Africa was founded in 2001 to strengthen mathematics and science education in Africa. It is now a continental association uniting ministries of education, teacher educators, researchers, and development partners in advancing STEM education. With a **vision** “*to be a leading organization in promoting quality STEM education in Africa*”, SMASE-Africa works through research, professional development, policy advocacy, and collaborative networks. Its mission is to “*To promote quality STEM education through research, capacity development, advancing policies, good governance, collaboration, and linkages in Africa.*”

From **2001 – 2013**, the regional conference was known as **SMASE-WECSA (Strengthening of Mathematics and Science Education in Western, Eastern, Central and Southern Africa)**. In **2014**, the forum was renamed the **Conference on Mathematics, Science and Technology Education in Africa (COMSTEDA)** to reflect its continental scope.

The **Conference on Mathematics, Science and Technology Education in Africa (COMSTEDA)** is SMASE-Africa’s annual flagship platform for dialogue, research dissemination, and professional exchange. Since 2014, COMSTEDA has rotated among member countries, bringing together educators, policymakers, NGOs, and the private sector to deliberate on innovations and challenges in STEM education. Its scholarly outputs are published in the *Journal on STEM Education in Africa (JSTEMEA; ISSN 2617-6300)*, of which this volume is the 6th edition.

COMSTEDA Editions

- **COMSTEDA 14** 2016, Nairobi, Kenya
- **COMSTEDA 15** 2017, Livingstone, Zambia
- **COMSTEDA 16** 2018, Maun, Botswana
- **COMSTEDA 17** 2019, Nairobi, Kenya
- **COMSTEDA 18** 2021, Virtual (hosted by Mozambique)
- **COMSTEDA 19** 2022, Blended (Kampala, Uganda)
- **COMSTEDA 20** 2023, Blended (Accra, Ghana)
- **COMSTEDA 21** 2024, Blended (Kaduna, Nigeria)
- **COMSTEDA 22** 2025, Blended (Lilongwe, Malawi)

The Objectives of COMSTEDA-22

The 22nd Conference on Mathematics, Science and Technology Education in Africa (COMSTEDA-22) was designed to:

1. **Provide a continental platform** for educators, governments, academic institutions, private sector, and development partners to interrogate issues and share best practices in STEM education.
2. **Improve the quality of education in Africa** by sharing impactful research findings and classroom practices that inform policy and practice.

3. **Present case studies and research outputs** that highlight innovative approaches in mathematics, science, and technology education across diverse African contexts.
4. **Promote and highlight the role of STEM education** in Africa's socio-economic development, aligned to Agenda 2063 and SDG 4.
5. **Foster networking, collaboration, and partnerships** among countries, institutions, and stakeholders to build collective capacity in STEM education.
6. **Interrogate emerging issues** such as ICT integration, artificial intelligence, equity, inclusion, and the competence-based curriculum shift, ensuring African learners are prepared for life challenges.



On behalf of SMASE-Africa and the Editorial Board, we present this first volume of the 2026 Edition of the Journal on STEM Education in Africa, containing fifteen research papers from COMSTEDA 22, Lilongwe. May these pages inspire, provoke, and guide collective action toward reimagining STEM for a Pan-African future.

Editorial

Article 1

Benson Banda, Yahaya Sani Rickagichikuni, Minata Redas and Jinga Andrew authored the paper titled: ***Integrating Indigenous Resources into STEM Skills Assessment: Cross-Disciplinary Design Patterns for African CBC***. This paper observed that Competence-Based Curriculum (CBC) reforms prioritised the development of practical skills and the ability to apply knowledge in authentic, culturally rooted situations, and that the integration of indigenous resources into STEM assessment tasks had emerged as a powerful strategy for grounding learning in African identity, local artistry and ecological sustainability. The study built on discussions from the AfriSTEMpedia WhatsApp dialogue held from 5 to 10 October 2025, complemented by interviews with STEM educators working in diverse schooling environments. It revealed that teachers were already experimenting with cross-disciplinary design patterns that embedded indigenous knowledge into competence-based assessment. Four patterns were prominent: the “heritage algorithm,” which used cultural symbols, indigenous numeracy and traditional measurement to cultivate algorithmic thinking; “eco-innovation,” which drew on the ecological wisdom of local materials such as plant fibres, clay and wood; “community engineering,” which linked STEM learning to everyday community technologies such as traditional irrigation, basket traps and grain storage; and “artistic STEM,” which blended creativity with scientific reasoning through African ornamentation and craftwork. The patterns were found to strengthen learner creativity, promote the inclusion of diverse cultural knowledge systems and open opportunities for school-based entrepreneurship. The study proposed guidelines emphasising the safe handling of indigenous materials, the accurate representation of cultural knowledge and deliberate interdisciplinarity in task construction, and concluded that CBC-aligned STEM assessments could become vehicles for culturally responsive, community-rooted and innovation-driven learning.

Article 2

Bridging Concepts and Reality: Enhancing Mathematics Instructions through Project-Based Learning for Upper Primary Schools Students by Fidele Ukobizaba, Jean Francois Maniraho and Alphonse Uworwabayeho explored how learners could be actively engaged in deep learning through Project-Based Learning (PjBL) in mathematics. The study employed a case study research design and collected data through classroom observation, focus group discussion and document review from 109 Grade Five (Primary Five) students purposively selected from one school in Nyamasheke District, Rwanda. The data were analysed thematically. The findings revealed students’ belief that PjBL made abstract concepts more concrete by allowing them to apply acquired concepts in real-world situations, and that their skills to collaborate and communicate mathematical concepts were enhanced. The study also highlighted students’ engagement as a pillar of active learning. Students’ ability to use instructional materials improved, although it remained at a low level, and a gap was found in their ability to ask or answer questions during or after presentations, which limited their critical thinking. The study recommended teacher training and the provision of enough local and contextualised instructional materials to bridge concepts with reality and make mathematics more relevant to students.

Article 3

Darius Katuka and Benson Banda, in the paper ***Integrating Preventive Maintenance (PM) into STEM Education: Centering African Sustainable Practices for Infrastructure Resilience in Zambian Learning Institutions***, explored how integrating Preventive Maintenance (PM) into STEM education could address the strain that rapid enrolment growth, following the introduction of free education from early childhood to secondary level in Zambia, had placed on school infrastructure. Drawing on African knowledge systems and communal care practices, the paper reframed PM as both a technical necessity and a pedagogical strategy to cultivate responsibility, sustainability and ecological awareness among learners. It noted that, despite a national maintenance policy dating back to 1977, school infrastructure had often been neglected because maintenance was perceived as peripheral, which limited hands-on skills development. The study argued that embedding PM in the curriculum would turn maintenance into experiential learning, strengthen competence-based education and foster indigenous values of stewardship, while practices such as energy-efficient use, repair-based culture, waste reduction and sustainable material management conceptually supported climate adaptation and mitigation. Its objectives were to develop context-appropriate PM strategies for schools, enhance human resource capacity through STEM-aligned training and promote cost-effective, locally informed maintenance systems. The findings highlighted the need to decolonise STEM education by institutionalising African sustainable practices, in line with the national vision of “caring for and handing over the best” to future generations.

Article 4

Peter M. Ndiritu authored the paper titled: ***STEM Pathway in Senior Schools: Developing Communication and Collaboration Skills by Learners in their STEM Projects***. The paper argued that the STEM pathway could prepare learners for the challenges of 21st century living by ensuring that they acquired effective competencies, among which communication skills were central, and observed that most learners were unable to communicate effectively in either written or oral form. The research examined how communication skills affected learners’ performance in their STEM projects by comparing their written and oral communication skills, scientific thoughts, methods and creativity in expressing learning outcomes. Data comprised four STEM subject categories, namely chemistry, biology, mathematics and physics, with fifteen projects per category. Written communication (Part A) was scored separately from oral communication (Part BC), and the two

were treated as dependent variables. Plotted against the number of projects per category, the two variables produced converging and diverging curves, while their combined scores produced a gradually declining line. The study explained that written communication demanded considerable time and effort for thinking and reflection, while anxiety, lack of confidence and limited practice opportunities impeded oral communication, and concluded that learners needed to develop both written and oral communication skills to convey their learning outcomes effectively.

Article 5

From Recall to Real: Transforming STEM Education Assessment in Africa through Competence-Based Learning by Benson Banda, Emanuel Omang Ocquaye, Ndege Samuel and Debra Mwango observed that African education systems were shifting from Outcome-Based Curriculum (OBC) to

Competence-Based Curriculum (CBC), anchored in constructivist and authentic learning paradigms that emphasised what learners could do rather than what they could recall, yet assessment practice had lagged behind curriculum policy. The study analysed multi-country qualitative data from 392 WhatsApp posts by 52 educators from ten African countries who took part in the AfriSTEM WhatsApp discussion held from 5 to 10 October 2025 and facilitated by the Directorate of Zambia's National Science Centre. Thematic analysis revealed three domains of transformation: redefining the purpose of assessment towards learning and empowerment rather than sorting; redesigning assessment tasks as authentic tasks in real or realistic contexts that measured knowledge, skills and values; and reconfiguring systems through policy reform, teacher professional development and moderation for trust. The paper recommended elevating formative assessment, integrating indigenous knowledge and developing an African-owned continental framework (CAF-Africa) for harmonising competence assessment across African states, and concluded that the sustainability of African STEM education reforms hinged on transforming how learning was assessed.

Article 6

Caroline Taliba, in the paper ***Concept-Driven Geometry Education: Enhancing STEM Learning through Constructivist Approaches***, examined how the 2023 Knowledge Co-Creation Programme (KCCP) course “Enhancing Teacher Professional Growth in STEM Education: Towards Effective STEM Learning Outcomes” transformed geometry education through a constructivist approach grounded in the Lesson Study model. The course developed a curriculum item and concept map for shapes that integrated two-dimensional (2D) and three-dimensional (3D) shapes from Early Childhood Education to societal contexts, treating 2D shapes as gateways to understanding complex 3D structures. The paper profiled gaps and challenges in mathematics curricula in Uganda and other African nations, including Botswana, Ghana, Malawi, Nigeria, Namibia and Zambia, and found that their syllabi focused on discrete topics rather than overarching concepts, leading to redundancy and missed opportunities for comprehensive understanding. The curricula emphasised conventional shapes while overlooking irregular objects prevalent in society and did not encourage the design and construction of products based on theoretical concepts. Drawing on the literature and on daily reflections from 11 participants, including teacher trainers, classroom teachers, in-service trainers and a curriculum designer, the study revealed significant repetition and surface learning and recommended that African curricula adopt concept-driven approaches.

Article 7

Peter Mulenga authored the paper titled: ***Unpacking Validity in Competence-Based Assessments through the 3H Model***. The paper noted that Africa's shift toward Competency-Based Curricula (CBC) reflected a continental commitment to education that fostered innovation, practical skills, values and sustainable development in line with Agenda 2063, yet assessment systems in many African countries remained anchored in colonial, recall-based traditions that weakened assessment validity. The study examined the validity of Competency-Based Assessment (CBA) practices in Zambia, Uganda, Kenya and Tanzania using teacher interviews, policy analysis and document review. Guided by the 3H Model of Head (cognitive), Hands (psychomotor) and Heart (affective), the study revealed that current assessments overemphasised knowledge recall while neglecting practical performance and values-based competencies. The integrated findings highlighted systemic gaps, including insufficient teacher capacity, limited application of indigenous knowledge and weak

alignment with holistic CBC goals. The study proposed an African-centred validity framework based on the 3H Model to strengthen CBA practices across the continent.

Article 8

Modernizing Mathematics and Science Education in Rwandan Secondary Schools Through Project-Based Learning by Jeannette Muterampundu, Ezechiel Nsabayeze, Aloys Iyamuremye, Venuste Nsengimana, Pheneas Nkundabakura, Theophile Nsengimana and Eugenie Uwamariya noted that improving mathematics and science education was pivotal to Rwanda's education reform, which emphasised Project-Based Learning (PBL), yet PBL implementation remained teacher-centred, constraining collaboration, critical thinking and problem-solving despite policy that advocated learner-centred approaches. Using a mixed research approach, the study collected data from 120 secondary school teachers through structured questionnaires and semi-structured interviews, and from 320 students through a 21st century skills questionnaire. Quantitative data were analysed using descriptive and inferential statistics, while qualitative data were analysed thematically. The findings revealed that teachers perceived PBL as highly effective in enhancing engagement (mean = 4.62) and conceptual understanding (mean = 4.54), with significant differences by teaching experience in favour of experienced teachers but no significant effect of gender or educational level. Three dominant themes emerged: the promotion of learner-centred practices, the need for ongoing professional support, and challenges related to limited teaching resources and time. The study concluded that PBL had transformative potential to modernise science and mathematics instruction, and recommended that teachers embrace PBL, that

policymakers prioritise systematic teacher training and adequate resources, and that future research explore the longitudinal impact of PBL on lifelong learning and entrepreneurial skills.

Article 9

Benson Banda, Anecetus Moonga, Eric Bbabbi and Muhydeen Ahmed, in the paper **Formative First: Rebalancing African Education Assessment Systems Toward Continuous Competence Measurement**, explored assessment practices across ten Science, Technology, Engineering and Mathematics (STEM) secondary schools in Zambia to establish the extent to which formative assessment was implemented and the systemic barriers that hindered its adoption, noting that African education systems continued to rely heavily on high-stakes summative examinations despite global reforms advocating formative, continuous assessment. Using a mixed-methods design, data were collected through surveys, interviews and classroom observations. The findings revealed a significant imbalance between formative and summative assessment practices, with summative approaches dominating instructional processes. Teachers demonstrated strong familiarity with summative examinations but limited capacity to design formative tasks and provide constructive feedback, and classroom observations showed minimal use of continuous assessment strategies, creating a gap between policy aspirations and classroom realities. The paper argued that this imbalance undermined competence-based curriculum reforms, particularly in STEM learning environments that required iterative feedback, and concluded that rebalancing assessment systems toward formative approaches was essential. It recommended strengthening national formative assessment policies, investing in teacher professional development and introducing digital tools to support feedback tracking.

Article 10

Empowering Women and Girls' Participation in Science, Technology, Engineering, and Mathematics (STEM) as Leaders of Africa's Sustainable Future by Nelson K. Koech explored strategies for empowering women and girls to participate and lead in STEM fields as a critical component of Africa's sustainable development, observing that gender gaps persisted in STEM education and careers despite numerous efforts. The paper sought to address systemic barriers to women's participation in STEM by analysing the effectiveness of policy reforms, mentorship programmes and inclusive pedagogies. It reviewed gender-responsive policy reforms across Africa, mentorship initiatives such as those led by African Women in Science and Engineering (AWSE), and inclusive teaching practices championed by institutions such as CEMASTEAM. Employing a qualitative comparative research design, data were collected through document analysis of reports from CEMASTEAM, UNESCO and various African ministries of education, and were analysed thematically, supported by basic descriptive statistics. Data from ten African countries were presented through charts and tables to visualise participation trends, implementation outcomes and access disparities. The findings revealed that, while notable strides had been made, challenges in implementation, access and sustainability remained. The paper recommended strengthening policy enforcement, expanding access to mentorship and enhancing gender-sensitive pedagogy, and underscored the necessity of systemic transformation to achieve gender equity and empower women as leaders in Africa's STEM future.

Article 11

Masuzyo Sibande and Chipso Namakau Sakala authored the paper titled: ***Uncovering Children's Abilities: A Case Study of Competence Development through Home-Linked Chores in an Early Learning Classroom***. This study explored how home-linked chores could serve as meaningful contexts for competence development in early learning classrooms, and examined how young children demonstrated and extended their abilities when engaged in familiar, real-life tasks such as washing, sweeping, arranging and simple cooking. A qualitative case study design was employed within an action-research framework. The target group comprised early childhood learners aged 4–6 years in a pre-primary classroom, with both boys and girls participating in structured practical activities, while parents were indirectly involved as contributors of materials and as post-activity informants. Data were collected through classroom observations, learner interviews and informal parent discussions. The findings revealed that the children exhibited higher levels of independence, initiative and collaboration than initially expected, and that through observation, imitation and peer learning they developed both fine-motor and social competences. Parents reported a positive shift in perception, acknowledging that their children were more capable and responsible than previously assumed. The study concluded that connecting classroom learning to home experiences through chores enhanced confidence, creativity and responsibility in early learners, and recommended that teachers intentionally integrate everyday home tasks into early learning environments to strengthen competence-based education.

Article 12

Isaac Sogbadzi, Daniel Ewusi-Essel, Mawuena Asem-Hanson and Heather Beem, in the paper ***Preliminary Findings from Piloting Low-Cost Engineering and Robotics in 7 STEM High Schools in Ghana***, reported on the work of Practical Education Network (PEN) with 25 teachers across seven

STEM schools that piloted the new engineering and robotics curricula introduced in 2023 by Ghana's National Council for Curriculum and Assessment (NaCCA) for Senior High and Senior High Technical Schools, which some teachers felt under-equipped to use. In November 2023, the government organised a two-week training at KNUST, which was followed by a year-long PEN-led programme of coaching and mentoring on hands-on learning with low-cost, locally available materials. Pre- and post-surveys showed gains in 13 of 14 competencies, with highly significant improvements in schematic symbols, computer-aided design, rapid prototyping, microcontroller programming and reading microcontroller data, and significant gains in areas such as ethics and safety, identifying components, multimeter use and flowcharts. Overall scores rose from 49.29 to 63.41. Interviews revealed that teachers gained confidence, observed greater student participation and reported stronger links between lessons and everyday life, while students

demonstrated curiosity and applied STEM concepts to practical projects. The study concluded that leveraging locally available materials to teach engineering and robotics proved impactful in Ghanaian classrooms and offered a pathway to decolonising STEM education in Africa.

Article 13

Sustaining the Ripple Effect: Educators' Cascading of Foundational Learning Environments following KCCP 2025 by Chipo Namakau Sakala and Natasha R. Nyangwe examined how educators who participated in the Knowledge Co-Creation Programme (KCCP) 2025 sustained and cascaded the theme of Foundational Learning Environments within their local contexts, seeking to understand the extent of implementation, the strategies used and the emerging impact on teaching and learning. A descriptive qualitative design was employed, focusing on post-training reflections and activity reports submitted by KCCP 2025 alumni from 14 African countries; reports were received from all fourteen representatives, and nine countries indicated active cascading of the theme. Data were collected through document analysis of the post-training reports, and thematic analysis identified common patterns, variations and success indicators across country contexts. The results revealed that educators successfully cascaded training concepts through structured in-service sessions, peer-learning communities and the integration of learner-centred pedagogies, while others created and redesigned learning spaces that enhanced inclusivity, the visibility of learning outcomes and hands-on engagement. The findings suggested that international professional development programmes such as KCCP could generate sustainable transformation when participants were supported to contextualise, disseminate and integrate competences that embedded a culture of co-creation and innovation in African education systems.

Article 14

Munashe Chakamanga, Tanya Dzinemarira and Tonderai Rusere, in the paper ***Investigating the Impact of Hands-On Laboratory Activities on Student Attitudes Towards Biology and Chemistry***, investigated the impact of inquiry-based, hands-on laboratory activities on secondary school students' attitudes towards Biology and Chemistry, noting that attitude was among the most important learning outcomes at this level because it shaped students' disposition towards a subject and the career aspirations they formed. The study addressed the lack of rigorous empirical evidence on whether intentionally designed laboratory sessions could improve attitudes in subjects that many

students regarded as abstract, content-heavy and unrelated to their lives. Five dimensions of attitude were analysed, namely enjoyment, perceived value, self-efficacy, reduction of anxiety and career interest, with data collected at three intervals from a group that received inquiry-based laboratory instruction and a group that followed traditional laboratory methods. The results revealed that inquiry-based laboratory teaching led to significant positive changes across all five dimensions, with the relative improvement greater in Chemistry, whereas the comparison groups showed only limited improvement. The study concluded that inquiry-based laboratories fostered curiosity, autonomy, confidence and long-term interest in science, and recommended their comprehensive adoption across Biology and Chemistry curricula, supported by professional development for science teachers in inquiry-based strategies, scaffolding and experimental design.

Article 15

Kalungwishi Elijah Kabemba authored the paper titled: ***Forming the Future Pan-African Learner through Transformative STEM: Bridging Identity, Innovation, and Sustainability for Agenda 2063***. Grounded in the GPS–DALE Macrophage framework, the paper argued that the COMSTEDA 22 theme, “Reimagining STEM for a Pan-African Future,” was semantically overloaded and risked reversing the authentic logic of transformation by prioritising system-level adjustments over human formation. Focusing on justice, competence, conscience, unity, sovereignty, healing, spirituality and morality, the framework conceptualised STEM reform as a pedagogical immune response rather than a technocratic fix, and positioned the African learner as the regenerative core of transformation. Drawing on African epistemological perspectives such as Ubuntu and Sankofa, cognitive load theory and the DALE Matrix, the paper built its arguments on findings from summative Senior Secondary STEM examination papers from Zambia (2000–2024), Ghana, Kenya, Rwanda, Uganda and South Africa. These findings revealed a systemic over-reliance on low-order skills, limited alignment with Agenda 2063 and SDG 4, and minimal attention to learner agency, innovation or continental consciousness. Using 18 diagnostic clusters, the paper analysed all five COMSTEDA sub-themes and proposed a reframed theme, “Forming the Future Pan-African Learner Through Transformative STEM,” in which reform began with the soul of learning rather than the shell of structure, presenting diagrams, cognitive heatmaps and healing rubrics as tools for regenerating African learning ecosystems.

ARTICLE 1

Integrating Indigenous Resources into STEM Skills Assessment: Cross-Disciplinary Design Patterns for African CBC

Benson Banda ¹, Yahaya Sani Rickagichikuni ², Minata Redas ³, Jinga Andrew ⁴

¹bensonbanda2003@yahoo.co.uk, ²yahayasanirickagichikuni@gmail.com,

⁴andrewjinga@gmail.com,

¹ Ministry of Education, Directorate of National Science Centre, ² National Teachers' Institute, Kaduna State, Nigeria ³ Zambezi Secondary School Zambezi, Zambia, ⁴ Pemba Secondary School, Pemba, Zambia

ABSTRACT

Competence-Based Curriculum (CBC) reforms prioritise the development of practical skills and the ability to apply knowledge in authentic, culturally rooted situations. Within this reform agenda, the integration of indigenous resources into STEM assessment tasks has emerged as a powerful strategy for grounding scientific and technological learning in African identity, local artistry, and ecological sustainability. By drawing on materials, techniques, symbols, and problem-solving approaches that communities have refined over generations, such integration strengthens the relevance of STEM education while encouraging learners to innovate from their cultural and environmental contexts.

This paper builds on discussions from the AfriSTEMpedia WhatsApp dialogue held from 5 to 10 October 2025, complemented by interviews with STEM educators working in diverse schooling environments. Insights from these conversations reveal that teachers are already experimenting with a range of cross-disciplinary design patterns that embed indigenous knowledge into competence-based assessment. Four patterns were particularly prominent. The first, referred to as the “heritage algorithm,” involves using cultural symbols, indigenous numeracy systems, and traditional measurement practices to cultivate algorithmic thinking and mathematical modelling. The second pattern, “eco-innovation,” centres on the ecological wisdom embedded in local materials such as plant fibres, clay, wood, and solar techniques, which learners can apply when developing sustainable scientific or engineering solutions. A third pattern, “community engineering,” encourages learners to draw inspiration from everyday technologies within their communities, including traditional irrigation methods, basket traps, grain storage structures, or herbal processing tools, thereby linking STEM learning to real social needs. The fourth pattern, “artistic STEM,” blends creativity with scientific reasoning by drawing on the rich traditions of ornamentation, craftwork, and aesthetic design in African cultures, enabling learners to explore STEM concepts through culturally meaningful artistic expression.

Across the dataset, these patterns were found to strengthen learner creativity, promote inclusion of diverse cultural knowledge systems, and open opportunities for school-based entrepreneurship. The findings underscore the importance of designing STEM assessments that are not only technically rigorous but also culturally authentic. To achieve this, the study proposes guidelines that emphasise safe handling of indigenous materials, accurate representation of cultural knowledge, and deliberate interdisciplinarity in task construction. Together, these insights highlight how CBC-aligned STEM assessments can become vehicles for culturally responsive, community-rooted, and innovation-driven learning.

Keywords: Indigenous Resources, Cross-Disciplinary Design, Heritage Algorithm, Community Engineering, Artistic STEM

1. Introduction

1.1 Background

Indigenous knowledge and local resources embody centuries of accumulated scientific observation, experimentation, and refined craftsmanship. Far from being static cultural artifacts, they function as living reservoirs of STEM intelligence that have been continuously adapted, tested, and transmitted across generations. Embedded in everyday practices, artistic traditions, and community technologies are sophisticated forms of problem-solving that mirror many principles taught in contemporary science, technology, engineering, and mathematics. These knowledge systems demonstrate that African communities have long engaged in rigorous empirical inquiry, optimisation of materials, and complex design thinking long before these processes were formalised in Western scientific frameworks.

One powerful example is the presence of fractals in African artistic and architectural traditions. From the recursive patterns of Ndebele mural designs to the terraced layouts of Ba-ila homesteads and the modular structure of traditional village planning, fractal geometry manifests through self-similarity, scaling rules, and recursive patterning. These designs illustrate intuitive mastery of mathematical concepts often considered advanced, such as iterative functions and proportional reasoning, making them ideal entry points for contextualised STEM learning. Similarly, the geometric symmetries present in basket weaving, pottery, beadwork, and mat-making reflect deep knowledge of spatial relationships, angle precision, tessellation, and structural stability. The artisans who produce these works rely on principles akin to those used in modern engineering and materials science: load distribution, tension control, reinforcement patterns, and optimisation of natural fibres for durability.

The practical ingenuity embedded in indigenous designs, whether in food preservation technologies, herbal distillation, rainwater harvesting, iron smelting, or traditional construction methods further demonstrates complex understandings of chemistry, environmental science, and mechanical engineering. These systems also reflect sustainable engineering practices that minimise waste, rely on renewable materials, and harmonise with local ecosystems.

Integrating such culturally grounded insights into formal STEM education enriches learning in several ways. It enhances conceptual understanding by linking abstract theories to familiar, tangible examples. It affirms learners' cultural identities and validates the scientific value of their environments. It promotes creative, hands-on problem-solving rooted in local realities. And most importantly, it supports a more inclusive, decolonised approach to STEM education one that recognises African intellectual traditions as legitimate sources of scientific knowledge. By situating STEM learning within indigenous knowledge systems, educators can create competence based assessments that are meaningful, contextual, and culturally responsive, while inspiring learners to innovate from their own heritage.

1.2 Problem Statement

Although CBC policies emphasise contextualisation, cultural relevance, and learner-centred pedagogy, they provide limited guidance on *how* educators can systematically embed indigenous knowledge and local materials into STEM assessment tasks. In practice, teachers are often left without structured design patterns, exemplars, or frameworks to support meaningful integration of indigenous resources within competence-based assessment (CBA). This gap results in inconsistent

implementation, underutilisation of rich local knowledge systems, and missed opportunities to create culturally responsive, community-rooted STEM learning experiences.

1.3 Objectives

1. Identify educators' experiences of using indigenous materials in STEM CBA.
2. Formulate cross-disciplinary design patterns reflecting African knowledge systems.
3. Recommend safety and ethical guidelines for implementation.

2. Research Questions

RQ1: What indigenous resource-based strategies are currently used in CBC-STEM assessment?

RQ2: Which cross-disciplinary patterns can organise this integration effectively?

RQ3: What safeguards are necessary for scale-up across schools?

3. Literature Review

Research on the integration of culture and STEM education highlights the longstanding presence of sophisticated mathematical and technological knowledge within African societies. Eglash (1999) illustrates this through his documentation of mathematical patterns embedded in African arts, crafts, and architectural forms, demonstrating that indigenous designs often reflect complex concepts such as recursion, symmetry, and algorithmic reasoning. Building on this work, Eglash later developed Culturally Situated Design Tools (CSDTs), which blend digital technology with cultural heritage to support the teaching of STEM concepts in ways that are meaningful and identity-affirming for learners (Eglash, 2016). Similarly, scholarship on indigenous knowledge integration emphasises that authentic learning grounded in local cultural contexts fosters creativity, relevance, and innovation, with Odora Hoppers (2002) arguing that such knowledge systems provide critical resources for transforming education.

Within contemporary pedagogical reforms, the Competence-Based Curriculum (CBC) further underscores the need for learners to demonstrate performance through tasks that are contextual, relevant, and grounded in real-world problem-solving. Assessment theorists such as Wiggins (1998) and Gulikers et al. (2004) highlight that authentic assessment requires tasks that mirror real-life practices and cultural realities. Together, these perspectives provide a strong theoretical foundation for integrating indigenous knowledge and cultural design principles into STEM assessment within CBC frameworks.

1. Methodology

1.1 Research Design

The study employed a *qualitative research design*, combining **thematic analysis** with **pattern synthesis**. This dual approach allowed for an in-depth exploration of how educators conceptualize and apply locally available or indigenous materials in STEM instruction. Thematic analysis facilitated the systematic identification of recurring ideas and meanings within the data, while pattern synthesis enabled the integration of these themes into broader interpretive insights that reflect emerging relationships, tensions, and instructional possibilities.

4.2 Data Sources

Data were drawn from two primary sources to ensure richness and triangulation: 1. **AfriSTEM-pedia WhatsApp Discussion Forum:** This platform provided naturally occurring conversations among STEM educators, where participants shared experiences, challenges, and examples of integrating indigenous materials into teaching. These spontaneous interactions offered authentic, practice-based insights.

2. **Semi-Structured Educator Interviews:** Individual interviews with selected STEM teachers allowed for deeper probing into participants' perceptions, motivations, and classroom practices. The interviews complemented the WhatsApp data by providing contextual details and clarifications.

4.3 Data Collection Procedures

WhatsApp discussions were exported in text format and anonymized before analysis, while interviews were audio-recorded with consent transcribed verbatim, and coded. The combination of conversational and interview data enabled a more holistic understanding of lived experiences and professional reasoning.

4.4 Data Analysis

The analysis followed a multi-stage qualitative process:

•Initial

Coding:

Texts were coded line-by-line to capture meaningful units related to the study focus. Four sensitizing codes guided the process: *oIndigenous materials* (e.g., clay, sticks, baskets, gourds, local crafts) *oIntegration* (ways these materials are incorporated into STEM lessons) *oSafety* (concerns or precautions in using natural or handmade materials) *oCreativity* (innovative instructional practices and learner engagement)

- Theme Development:** Codes were clustered into broader categories based on conceptual similarity. This process was inductive, allowing themes to emerge naturally from participant contributions rather than being predetermined.
- Pattern Synthesis:** Higher-order patterns were generated by examining how themes interacted across data sources. This step involved searching for cross-cutting concepts—for example, the relationship between material availability, safety considerations, and opportunities for creative STEM learning.
- Interpretation:** The resulting patterns were interpreted in relation to existing literature on Indigenous Knowledge Systems (IKS), contextualized STEM pedagogy, and resource-constrained learning environments.

4.5 Trustworthiness

Credibility was enhanced through triangulation of data sources (WhatsApp discussions and interviews) and iterative coding checks. Member checks were performed with a subset of participants to validate interpretations.

5. Findings (with verbatim excerpts)

Theme 1: Indigenous materials enhance access and creativity

i. “Learners use clay to model molecular structures—simple but powerful.” — Participant 68 (06/10/2025 09:41 am)

ii. “Maths through basket designs connects tradition with geometry.” —

Participant 74 (06/10/2025 09:49 am)

Theme 2: Cross-disciplinary learning emerges naturally i. “In one task, students built solar cookers using bamboo; physics met sustainability.” — Participant 71 (06/10/2025 09:43 am)

ii. “When art, science, and environment join—learners become innovators.” —

Participant 69 (06/10/2025 09:42 am)

Theme 3: Safety and ethics matter

i. “Local doesn’t mean unsafe; schools must guide material selection.” —

Participant 176 (07/10/2025 12:16 am)

6. Discussion

Educators consistently affirm that the integration of indigenous resources into STEM learning environments enhances learner engagement, deepens conceptual understanding, and sparks innovative thinking. By drawing on familiar cultural materials, artistic traditions, and community-based technologies, teachers report that learners become more motivated and confident, seeing themselves reflected in the content they study. This pedagogical approach extends Eglash’s concept of heritage algorithms, which illustrates how cultural patterns embody mathematical logic, by broadening the lens to include scientific reasoning, ecological knowledge, engineering practices, and artistic expression grounded in local identity. In this expanded view, indigenous resources act not only as cultural artefacts or teaching aids but as gateways to blended STEM competencies rooted in lived experiences.

Integrating such resources into assessment tasks directly operationalises the CBC’s demand for holistic competence, where learning is demonstrated not merely through recall of information but through meaningful performance. This includes cognitive competence (understanding concepts through culturally relevant examples), practical competence (applying skills using local materials, tools, or community technologies), and social competence (collaborating, valuing cultural knowledge, and solving problems relevant to one’s context). Through this lens, indigenous knowledge becomes a dynamic pedagogical asset that supports learners in connecting theory to practice, strengthens cultural identity within STEM disciplines, and nurtures creative, context-responsive forms of innovation.

7. Cross-Disciplinary Design Patterns

Pattern Name	Core Idea	Representative Task	Assessment
Heritage Algorithm	Mathematical principles in art & design	Analyse symmetry in traditional weaving; apply fractal geometry	
Eco-Innovation	Sustainability via local materials	Construct solar dryer using bamboo or clay tiles	
Community Engineering	Solving community challenges	Design low-cost water filters from local resources	
Artistic STEM	Expressive creativity & technical design	Build instruments applying sound-wave physics	

The study identified four recurring design patterns that illustrate how indigenous knowledge can be meaningfully integrated into CBC-aligned STEM assessment. The first pattern, Heritage Algorithm, draws on the mathematical principles embedded in traditional art and design. Tasks under this pattern encourage learners to analyse symmetry, proportionality, and recursive structures present in cultural artefacts such as woven mats, beadwork, or mural patterns. For example, an assessment may require students to examine the geometric logic behind a traditional weaving design and then apply concepts of fractal geometry or transformational symmetry to model or recreate the pattern. This approach promotes mathematical reasoning while validating cultural artistry as a source of authentic STEM knowledge.

The second pattern, Eco-Innovation, centres on sustainability and the creative use of locally available materials. Here, learners engage with ecological knowledge and renewable materials that reflect community practices. A representative assessment task might involve designing and constructing a solar dryer using bamboo, clay tiles, or other indigenous resources. Through such tasks, learners demonstrate competence in energy science, materials engineering, and environmental stewardship, while exploring contextually relevant solutions to real problems. The third pattern, Community Engineering, positions learners as problem-solvers addressing practical challenges within their communities. Tasks in this category require the application of scientific and engineering principles to develop low-cost, locally appropriate technologies. For instance, learners may design a water-filtration device using natural materials such as charcoal, sand, and gravel, drawing from both indigenous techniques and scientific testing. This pattern highlights CBC's emphasis on functionality, collaboration, and social responsibility.

The fourth pattern, Artistic STEM, blends expressive creativity with technical design. It recognises that artistic traditions are deeply intertwined with physics, acoustics, structural design, and material science. An illustrative assessment might ask students to build a simple musical instrument—such as a drum, shaker, or stringed device—using local materials while explaining how sound-wave physics influences pitch, resonance, and vibration. This pattern encourages learners to merge aesthetic expression with scientific explanation, embodying a holistic approach to competence development.

Together, these patterns show how indigenous resources can anchor STEM learning in culturally meaningful, interdisciplinary, and practically oriented assessment tasks that fully align with the goals of the Competence-Based Curriculum.

Each design pattern simultaneously addresses several key CBC competences, offering a multidimensional learning experience. Cognitively, the patterns promote deeper understanding of STEM concepts by situating abstract ideas within familiar cultural frameworks. Psychomotor skills are strengthened as learners manipulate local materials, construct artefacts, and engage in hands-on experimentation aligned with real-world practices. The affective dimension is activated through cultural affirmation, increased motivation, and a sense of belonging that emerges when learners see their heritage valued in the classroom. In addition, the patterns cultivate entrepreneurial competence by encouraging learners to recognise the economic potential of indigenous technologies and crafts, inspiring them to design marketable innovations rooted in local knowledge systems. Collectively, these competencies reflect the holistic intent of CBC, where learning is not isolated to academic mastery but extends to practical capability, personal identity, and community-responsive creativity.

8. Recommendations and Implications

Policy

- a. Include indigenous-resource guidelines in CBC assessment syllabi.
- b. Support local teacher-resource networks to document safe material alternatives.

Practice

- a. Use project-based learning incorporating indigenous artistry.
- b. Moderate tasks for cultural sensitivity and local feasibility.

Implications

Integrating indigenous knowledge elevates STEM assessment from imitation to innovation, anchoring education in African identity and sustainability.

9. Conclusion

At its core, the Competence-Based Curriculum (CBC) must not only measure what learners know, but also celebrate what they can *do* with the collective knowledge, materials, and wisdom of their communities. When assessments draw meaningfully on indigenous resources, they transform learning into an active, culturally grounded process that allows learners to demonstrate creativity, problem-solving, collaboration, and real-world application. Such cross-disciplinary integration illustrates competence in its fullest form—where cognitive understanding merges with practical skill, cultural identity, and community relevance. It affirms that African heritage is not peripheral to STEM, but a vibrant source of algorithms, materials science, ecological knowledge, artistic geometry, and engineering ingenuity. By embedding these Indigenous Knowledge Systems into CBC-aligned assessment, educators cultivate learning experiences that are creative, inclusive, sustainable, and authentically African, while empowering learners to innovate from the strengths of their own heritage.

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ARTICLE 2

Bridging Concepts and Reality: Enhancing Mathematics Instructions through Project-Based Learning for Upper Primary Schools Students

Fidele Ukobizaba, Jean Francois Maniraho and Alphonse Uworwabayebo

ukobizabafidele51@gmail.com, ukobifidele@gmail.com

African Centre of Excellence for Innovative Teaching and Learning Mathematics and Science (ACEITLMS),
University of Rwanda-College of Education (UR-CE), Kayonza, Rwanda

ABSTRACT

A variety of teaching and learning strategies have been implemented to explore how learners can be actively engaged in deep learning to develop knowledge and skills. This study employed a case study research design to collect data from classroom observation, focus group discussion, and document review from 109 Grade Five (Primary Five) students purposively selected from one school of Nyamasheke district, Rwanda. Data were analyzed thematically. The findings revealed in students' beliefs that PjBL makes abstract concepts more concrete by allowing students to apply acquired concepts in real world situations. It was found that through PjBL, students' skills to collaborate and communicate mathematics concepts were enhanced. The study also highlights the importance of students' engagement as a pillar of active learning. The students' adaption to use instructional materials was enhanced, but this skill is still at a low level, as shown by the results from document analysis. A gap was also found in students' ability to ask or answer questions during or after the presentation, preventing their critical thinking. The study recommends the teacher's training and provision of enough, local, and contextualized instructional materials to bridge concepts with reality and make mathematics more relevant to students.

Keywords

; Communication skill, creativity skill, critical thinking skill, project-based learning, real-world problem solving.

Introduction

Mathematics is known for its privileged role of being used as a tool to solve real-life problems. That reason mathematics is known as a tool often used in different science and engineering disciplines. Mathematics plays a crucial role in a country's economic development. This is because a nation's economic growth depends on producing mathematically literate man powers (Ministry of Education [MINEDUC], 2018). For instance, many Western countries such as France, the United Kingdom, Belgium, United States of America fall far behind the economies of East Asian countries such as Singapore, China, Taipei, and Korea, whose student's achievement in mathematics is higher (Bethell, 2016). The improvement of mathematics instruction at both primary and secondary levels is crucial for the country to be competitive at the global economic level.

A variety of teaching and learning strategies have been implemented to explore how learners can be actively engaged in deep learning to develop knowledge and skills. According to Ukobizaba et al. (2019), mathematics researchers must conduct research on the application of mathematics at different grade levels to help researchers and practitioners understand the relevance of mathematics

concepts in real-life situations. In this regard, Verschaffel et al. (1999) created twenty problem-solving-oriented lessons for grade five learners for over four months. Also, Çakici (2013) employed project-based practices to investigate the effect of Project-Based Learning approach on children's achievement and attitude in science. These researchers aimed to determine the effect of active learning strategies on students' performance and real-world problem-solving abilities. The present study was interested in the use of the project-based learning method as one of the learner-centered approaches that enhance students' active learning towards students' knowledge and skills development.

Project-based learning is an instructional methodology that has gained significant attention recently due to its potential to enhance students' knowledge and skills development in different subjects. Project-based learning presents a viable and effective pedagogical approach to promoting active, meaningful, and contextualized learning experiences (Han et al., 2016) as opposed to the traditional methods, which often emphasize rote memorization and procedural fluency. Instead, PjBL helps to bridge this gap by providing concrete, hands-on experiences that make mathematics more accessible and relevant to students' lives (Haatainen & Aksela, 2021). In mathematics education, PjBL can help students understand complex concepts by connecting abstract mathematical ideas to real-life situations, enhancing their comprehension and retention of knowledge (Çakici, 2013; Pan et al., 2021). In addition, this teaching strategy encourages active learning, critical thinking, and applying knowledge in practical contexts, making learning more engaging and effective (Han, et al., 2016).

The introduction of PjBL in mathematics education aligns with Rwanda's broader educational goals, which include promoting active learning, critical thinking, and the practical application of knowledge (MINEDUC, 2018). Within the same vein, integrating PjBL into mathematics instruction supports the goals of the competence-based curriculum (CBC) which intends to foster cognitive, creativity, and social skills such as collaboration and communication (Khalaf & Alshammari, 2023). In this context, PjBL allows students to learn collaboratively from one another and benefit from diverse perspectives, which is particularly important in classrooms where students may have varying levels of prior knowledge and skills (Juuti et al., 2021). Additionally, the focus on real-world mathematics applications can help clarify the subject and reduce mathematics anxiety, which is a common barrier to student success (Ukobizaba et al., 2021). Thus, PjBL has the potential to provide students with opportunities to apply the acquired knowledge in the classroom by engaging them in meaningful learning experiences.

Because learning by doing produces more lasting results than simply listening to a lesson (Pan et al., 2021). Students can acquire knowledge and skills that are more permanent and make mathematics concepts more relevant by implementing different projects by students. In this way, students have a chance to materialize abstract concepts, gather examples from real life, and relate those examples to various disciplines. Through social-constructivism theory, students are provided opportunities to interact, identify problems, discuss about the issues, and suggest solutions. According to social constructivism, social elements influence the way groups of individuals construct their understanding and formal knowledge while engaged in learning processes (Han, et al., 2016). To fill the gap linked to traditional teaching method whereby students simply memorize abstract concepts, a case study research design was employed to investigate the effectiveness of the PjBL approach on students' knowledge and skills development. By exploring the knowledge and skills students gain, this study

aims to understand the students' perceptions and experiences related to PjBL. The following research questions guide this study:

1. What are the knowledge and skills developed in students due to project-based learning incorporation into mathematics instructions?
2. What are the challenges experienced by students during mathematics instructions through project-based learning?
3. How should project-based learning be effectively incorporated to enhance students' knowledge and skills development?

Methodology

Research design

This study employed a case study research design (Cresswell, 2018) to explore the students' lived experiences when exposed to project-based learning pedagogy. Mixed methods were used to collect both qualitative and quantitative data. A case study provides a rich context, making it possible to explore variables in real-life settings that might be difficult to examine through other research methods (Flyvbjerg, 2011). By adopting a case study, this study provides a nuanced understanding of challenges linked to the incorporation of project-based learning teaching methods in mathematics instructions and the adequate measures necessary to implement this innovative pedagogy effectively.

Participants, sampling, and setting

A qualitative case study was employed in one selected secondary school in Nyamasheke district, Western province of Rwanda. This school holds 12 years of basic education (12YBE). The school has different educational levels, including pre-primary, primary, lower secondary, and advanced level. The school was purposively selected because it has a primary school level. In addition, the school was selected because it is located in the researcher's neighborhood, which financially facilitated the main author to collect data on a regular basis. The study employed 119 P5 students (54 boys and 65 girls). They were in the third term of the 2023-2024 Academic Year. These students were taught Units 11 and 12. The content for Unit 11 is "Drawing and constructing angles," while for Unit 12, the content is "Interpreting and constructing scales drawing". The study involved a teacher who was purposively selected because he is teaching mathematics in the upper primary at the selected school.

Research Instruments

A Lesson Observation Tool for Project-based Learning (LOTPBL) was developed by the main author and used to collect data. The tool was developed based on social constructivism learning theory (Jumaat et al., 2017; Nwafor et al., 2012). The social constructivism learning theory contends that people construct knowledge socially through collaboration and communication (Akpan et al., 2020). To check the instrument reliability, the main author and three research assistants watched and rated three videos independently. The IRR generated in the second phase was 88% with a Cohen Kappa coefficient of 0.8. This value of Kappa is a strong level of agreement indicating that the tool is worthy to collect reliable data (McHugh, 2012). The tool is made of 25 items. Each item has two

options, “Yes” or “No” under which the cell is marked to inform whether an activity “occurred” or “did not occur” respectively, during instructions.

Data collection and analysis

The data collection process followed professional practices and ethical considerations. This involved obtaining a research clearance letter from the UR-CE Research Screening and Ethics Clearance Committee (RSEC-C) through the University of Rwanda Directorate of Research and Innovation (UR-DRI) with reference number Ref: DRI-CE/031(a)/EN/gi/2024. Before data collection, the participant teacher signed an informed consent. The participants were ensured of trustworthiness, confidentiality, and anonymity during the research process. Items from LOTPBL had two options; “Yes” or “No” which were scored “1” or “0”, respectively. Thematic analysis was used for qualitative data obtained from FGD and documents (students’ notebooks). Taguette software was used to analyze qualitative data (Rampin & Rampin, 2021).

Results

The results are presented based on six themes identified based on data collected from classroom observations, FGDs, and document analysis. (1) Students enhanced conceptual understanding due to project-based learning, (2) Students’ communication during project-based learning instructions, (3) Students’ adaptation and creativity during project implementation, (4) Experienced challenges during mathematics instructions, and (5) Effective implementation of project-based learning in mathematics instructions. Results are presented following the research questions.

Theme 1: Students enhanced conceptual understanding

Project-based learning helps students develop both conceptual and practical skills through real-world problem solving. Through hands-on projects, students develop conceptual understanding of mathematics by applying them in real contexts rather than memorizing them. At the beginning of exposing students to PjBL, students showed a low level of conceptual understanding. For instance, students marked randomly angles within shapes as long as the total interior sum up to 360 degrees.

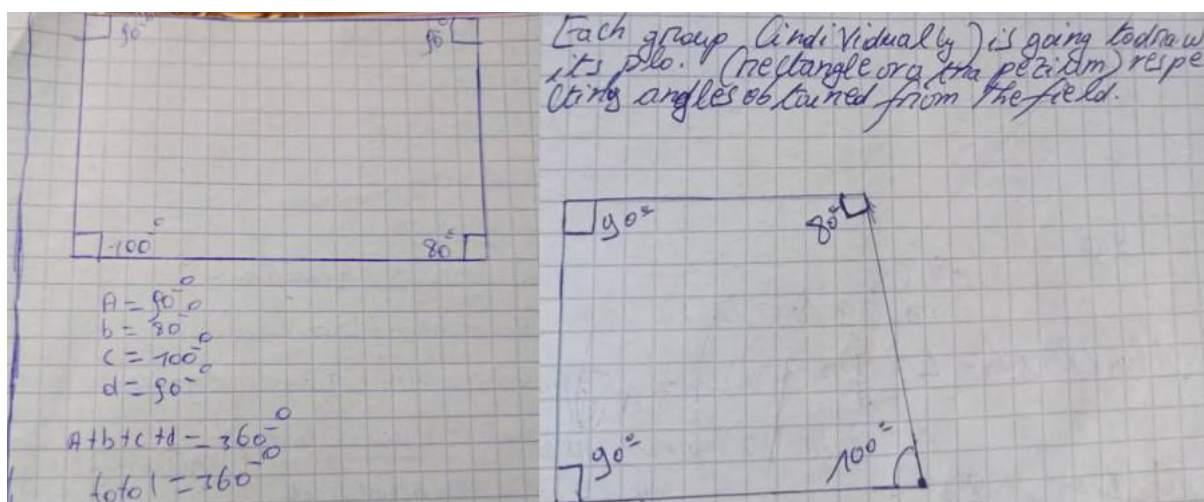


Figure 1: Student’ work activity about interior angles within a rectangle and a trapezium

As shown in Figure 1, for two figures; a rectangle and a trapezium, students put incorrect angles within the shapes. However, the sum of interior angles is 360 degrees. This shows that students have

memorized the concept and lack skills in measuring angles correctly using mathematics tools. Project-based learning plays a crucial role in providing students with opportunities to use different instructional materials while implementing projects and solving real-world problems. Through the intervention by the researcher in collaboration with the teacher participants, students were supported and showed how to use materials needed for the project effectively. The following is an example (Figure 2) showing where a student marked correct angles after drawing the land plot in a notebook.

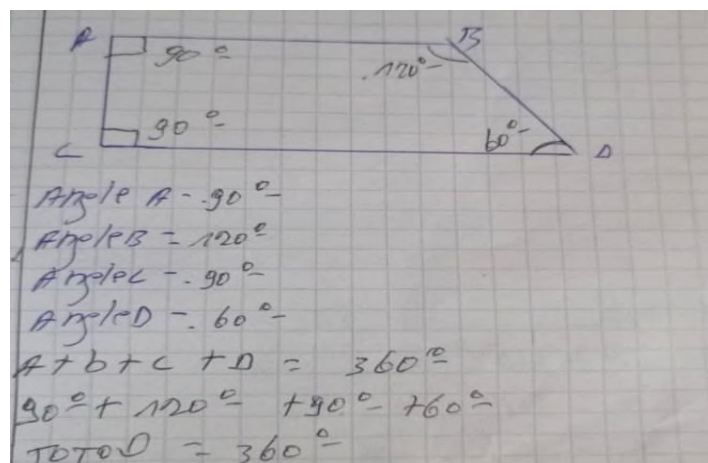


Figure 2: Student' work showing the correct measurement of angles

Figure 2 represents the students' work about measuring angles in 2D-shape. Students measured and put the interior angles of the shape. While measuring, students learned at the same time the concept of finding the sum of interior angles of any quadrilateral, which adds to 360 degrees. In this regard, students have transferred the knowledge acquired in class to real situations and vice versa. The students' effective use of instructional materials is still at a critical level. These results indicate that students were not confident enough to use and interact with instructional materials.

Project-based learning gradually impacts learning. The learning progress is often seen over time as students become more accustomed to the method (Pan et al., 2021). PjBL helps students deepen their conceptual understanding through engagement with authentic problems (Miller & Krajcik, 2019). PjBL enhances conceptual learning; more structured support is needed when it comes to technical skill development, such as using mathematical instruments (Haatainen & Aksela, 2021).

Theme 2: Students' communication, during project-based learning instructions

Unlike the traditional teaching methods, PjBL actively involves students in meaningful tasks requiring students' teamwork, collaboration, and critical thinking. The results from classroom observation showed that students were actively engaged and collaborative in implementing their project. For instance, students worked together to solve problems, such as ensuring the sum of measured angles added up to 180 degrees for a triangle and 360 degrees for a quadrilateral. The spirit of teamwork was also shown in students when they contributed ideas and discussed their findings before the presentation. This collaboration justifies the effectiveness of PjBL in enhancing teamwork and collaboration (See Figure 3).

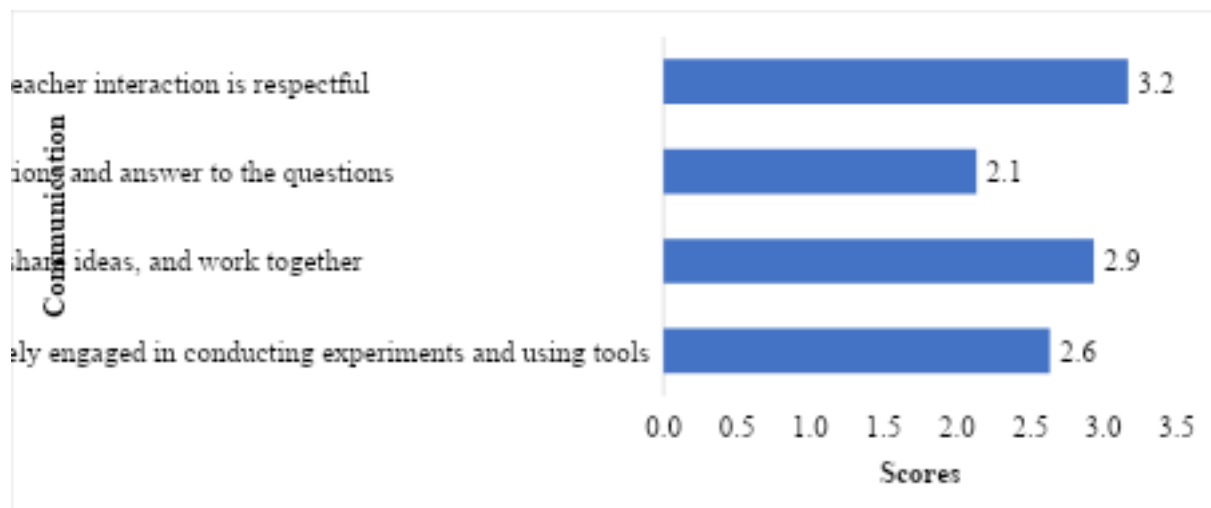


Figure 3. Observed students' skills in communication during project-based learning instructions

Figure 3 presents observed students' communication. The results from Figure 3 show that student interaction was extremely well done, with 3.2 out of 4 scores. This was followed by students sharing ideas and working together, also found to be very well done with 2.9 out of 4 scores. However, students' abilities to use instructional materials, asking and answer asked questions were scored at 2.6 and 2.1 out of 4 scores, respectively. These results are at a medium level and inform that there is a need for improvement. Project-based learning is known for creating a collaborative learning environment where students critically think through discussions to find solutions to problems.

The results from the classroom observation have shown an emphasis on the active and collaborative nature of Project-Based Learning (Khalaf & Alshammari, 2023). Han, Capraro, et al. (2016) observed that PjBL fosters student engagement through hands-on activities. Students using resources like protractors and rulers during PjBL also reinforces the notion that authentic tasks help learners to connect theoretical knowledge with real-world applications (Sukacké et al., 2022). As was also confirmed during focus group discussions with students, collaboration and communication stood out as major benefits of PjBL, whereby students reported that they found it easier to work together and explain mathematical ideas during group tasks. This learning environment echoes findings from social learning theories, which suggest that peer interaction and collective problem-solving play a critical role in cognitive development (Dowell et al., 2020).

Theme 3: Students' creativity during project implementation

An effective use of the mathematics tools enhanced students' ability to apply mathematical concepts in practical scenarios, which reinforced their learning outcomes. Although students struggled with using mathematical tools, students demonstrated creativity and improvisation in using available materials after assistance from the participant teacher and peers. For instance, students managed to fix sticks and tie a rope/thread with a little assistance to make the land plot into either a triangle or a rectangle shape. Students managed to convert measures from meters to centimeters. Students were trying to take a ruler appropriately to draw diagrams (measurements of the class).

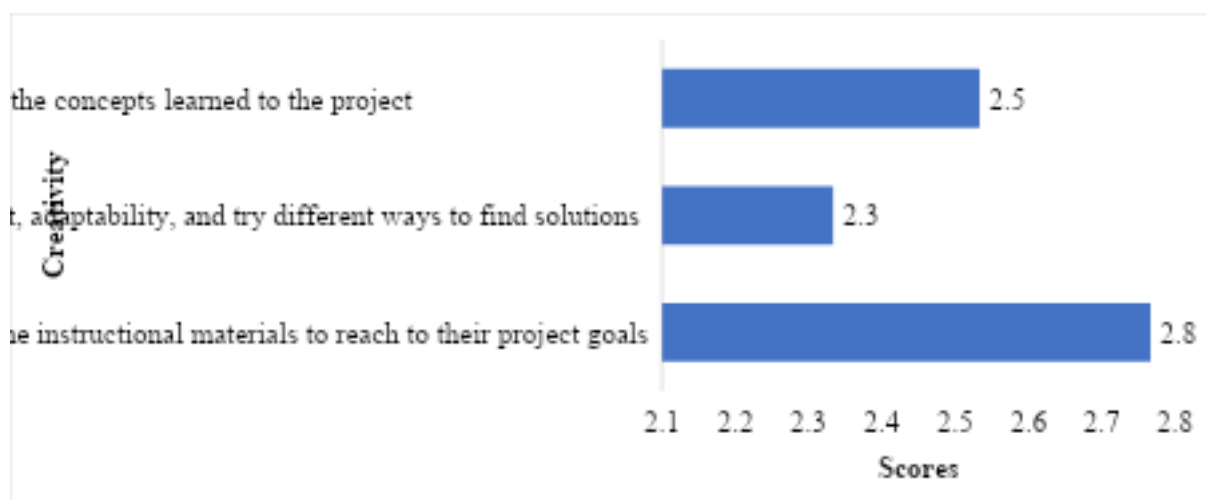


Figure 4. Observed students' skills in creativity during project-based learning instructions

Figure 4 shows the students' creativity during the project implementation. The students' adaptation looked at the extent to which students use instructional materials correctly, their abilities to use different ways while finding solutions, and their abilities to apply learned concepts to real-world situations. The results showed that the students' adaptation is at a medium level since none was scored at 3 out of 4 and above. A very low level was found on the item of students' confidence and ability to use different ways in finding solutions scored 2.1 out of 4. These results indicate the lecturing method often used in schools, which often promotes students to memorize procedures.

Theme 4: Experienced challenges during mathematics instructions

Despite the overall positive experience with PjBL, several challenges were observed. While participating in PjBL activities, students faced several challenges, such as disagreements within groups, difficulties in presenting their work, and unfamiliarity with using instructional materials such as rulers and protractors. During a focus group discussion, Student One declared,

"Presenting in a class was a challenge. Some were worried about what they were going to be presented. Sometimes, we could forget what to present. We could not respect real measurements." For some, measuring angles and handling the protractor was particularly challenging, as they struggled to hold the tools correctly or read the measurements accurately (FGD: 17 February 2025)."

Another reported challenge was students' difficulties in measuring land plot lengths and angles accurately. Common issues included confusion between meters and centimeters, difficulties in holding a protractor correctly, and problems in pulling and securing a rope for measuring land plots. For instance, Student Two during FGD reported,

"Measuring 90 and 45 degrees using a protractor was a challenge at first. Any angle we measured, we recorded 90 degrees. We could not hold the protractor appropriately. The teacher came and showed us how to measure effectively using a protractor. We showed the teacher what we wrote in our notebooks. When the teacher finds it wrong, he corrects it (FGD: 17 February 2025)."

Additionally, some students found it difficult to present their findings in front of the class, which led to anxiety and hesitation. Students explained, *"Although we had to agree on what to present, none was ready to write the work and present. In Mathematics, it was the first time for us to present."*

The reported challenges by students highlight the need for more practice and support in using mathematical tools and building in students' confidence in public speaking.

Theme 5: The effective implementation of project-based learning in mathematics instructions

Students showed the ability to propose a project. Students showed what an ideal PjBL should look like for them. In their explanations, students recognize the relevance of real materials during the instructions. They are aware that using real instructional materials enhances their conceptual understanding. Giving an example of Unit 11 (Constructing and measuring angles), students argued that a mathematical set is an important need. Giving an example on Unit 9 (money), students advised that the teacher should bring real money. Students said that the teacher can propose a project entitled "Saving". To implement the project, the teacher can create a scenario where one student will act as a buyer and another a seller. The student Four during FGD argued,

"For example, the next unit is Unit 9: Money. The teacher should bring real money (cash). The teacher should teach using real objects whenever possible. The teacher can create a scenario. For instance, the teacher can give 20000 Frs to a student and ask that the student take 5000 Frs and assume that it is used for transport. The teacher can ask students to find the remaining money (the balance) in hand (FGD: 17 February 2025)."

To effectively implement PjBL, enough relevant materials should be available for students to use. The teacher, as a facilitator of the lesson, should always support students and show them how to use different instructional materials. Research suggests that while PjBL fosters independent learning, some students may struggle with technical tasks without sufficient scaffolding (Aldabbus, 2018). Therefore, teachers are expected to play a critical role in bridging this gap by providing additional support and feedback during the learning process. This will highlight the balance required in PjBL between student autonomy and instructional support, ensuring that students engage with the content and master the necessary skills to apply their knowledge effectively.

Conclusion and implications

The results of this study highlight the effectiveness of Project-Based Learning (PjBL) in fostering students' knowledge and skills development. Students believe that PjBL contributes greatly to their conceptual understanding, making learning vital while solving real-world problems and preparing them for future career success. The active participation and hands-on activities observed in the classroom demonstrate that PjBL creates a dynamic and interactive learning environment where students can better understand abstract mathematical concepts through real-world applications. However, challenges such as the correct use of mathematical tools, like protractors and rulers and other mathematics tools, reveal the need for additional guidance in specific skill development. Thus, while PjBL promotes conceptual understanding and structured support from teachers, the provision of sufficient instructional materials is crucial to help students accurately apply their knowledge. From a policy perspective, educational systems should consider incorporating PjBL more widely across the curriculum to foster student communication and real-world application of mathematical concepts. This study recommends teacher training programs include specialized sessions on scaffolding techniques for PjBL. This study was conducted in one school selected from the Nyamasheke district, which may not allow the generalizability of findings.

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ARTICLE 3

Integrating Preventive Maintenance (PM) into STEM Education: Centering African Sustainable Practices for Infrastructure Resilience in Zambian Learning Institutions Darius Katuka, Benson Banda

Directorate of National Science Centre, Ministry of Education, Lusaka, Zambia dariuskatuka@gmail.com, ben-sonbanda2003@yahoo.co.uk

ABSTRACT

Education is a cornerstone of national development and individual empowerment. In Zambia, the implementation of free education from early childhood to secondary level demonstrates a commitment to inclusivity and equity, aligned with Sustainable Development Goal 4 and the Continental Education Strategy for Africa (CESA). Rapid enrolment growth has strained the capacity of learning institutions to maintain safe, functional infrastructure, compromising teaching and learning quality. This study explores how integrating Preventive Maintenance (PM) into STEM education can address these challenges by promoting infrastructure resilience, environmental sustainability, and indirectly supporting climate-change mitigation. Drawing on African knowledge systems and communal care practices, PM is reframed as both a technical necessity and a pedagogical strategy to cultivate responsibility, sustainability, and ecological awareness among learners. Despite Zambia's national maintenance policy since 1977, neglect of school infrastructure, often due to perceptions of maintenance as peripheral, limits hands-on skills development. Embedding PM into the curriculum transforms maintenance into experiential learning, strengthens competence-based education, and fosters indigenous values of stewardship. Practices such as energy-efficient use, repair-based culture, waste reduction, and sustainable material management conceptually support climate adaptation and mitigation, though their quantitative environmental impact is not measured in this study. The objectives are to (a) develop context-appropriate PM strategies for schools, (b) enhance human resource capacity through STEM-aligned training, and (c) promote cost-effective, locally informed maintenance systems. Findings highlight the need to decolonize STEM education by institutionalizing African sustainable practices that equip learners with modern competencies grounded in cultural and ecological resilience. This approach reinforces Zambia's education reforms and advances the national vision of "caring for and handing over the best" to future generations, while implying potential contributions to climate-smart school management.

Keywords: Preventive Maintenance, STEM Education, Learning Institutions, Sustainability, Infrastructure Resilience, African Knowledge Systems

1. Introduction

Education is not only a fundamental human right but also a key instrument for national development and individual empowerment. In Zambia, the implementation of the free education policy reflects the nation's alignment with global goals like SDG 4 and Agenda 2063. However, the expansion of enrolment has not been matched by sustainable infrastructure investments. The neglect of maintenance has led to deteriorating institution environments. This paper argues for the integration of Preventive Maintenance (PM) into STEM education as both an infrastructure solution and a pedagogical tool that draws from indigenous practices and promotes resilience and responsibility among learners.

Preventive Maintenance (PM) in a STEM educational institution is the systematic, scheduled, and documented performance of inspection, cleaning, calibration, lubrication, part replacement, and minor adjustments on equipment, tools, instruments, and facilities before failure occurs, to ensure operational reliability, safety compliance, accuracy of results, and longevity of assets in support of uninterrupted hands-on learning, research, and innovation activities (STEM Education Maintenance Task Force. (2025).

1.1. Rationale and Policy Alignment

To strengthen this integration, the study draws upon the following national and international policies: Zambia's 1977 Education Reforms laid an important foundation for the integration of productive work into institution life. These reforms recognized the value of combining academic learning with practical activities to develop well-rounded learners equipped with both intellectual and technical skills. A critical aspect of this vision was the emphasis on teacher professionalism, ensuring that educators were not only content experts but also facilitators of practical, skill-based learning. Building on this philosophy, the national education policy "Educating Our Future" (1996) further recommended that infrastructure maintenance be treated as a necessary and planned activity within the institution system. It emphasized that maintenance should be budgeted for and integrated into the curriculum to provide learners with hands-on experiences in real-world problem-solving, especially within science, technology, engineering, and mathematics (STEM) disciplines.

Zambia's Vision 2030 builds on these earlier reforms by identifying poor infrastructure maintenance as a major barrier to achieving quality education. It promotes the integration of technical and vocational education and training (TVET) as a strategy to equip learners with practical skills necessary for national development. Preventive maintenance, in this regard, is seen as both a necessity for sustaining educational facilities and a valuable learning opportunity in technical fields. This vision is further operationalized in the Eighth National Development Plan (8NDP) for 2022–2026, which highlights key priorities such as skills development, environmental sustainability, and the integration of information and communication technologies (ICTs) into education. The 8NDP calls for improved infrastructure management and the creation of conducive learning environments that prepare learners for the challenges of a modern economy. At the continental level, the African Union's Agenda 2063 envisions a skills revolution driven by the expansion of STEM education, emphasizing self-reliance, entrepreneurship, and sustainable development. It encourages African countries to invest in education systems that are responsive to societal needs and capable of producing innovators and problem-solvers. In alignment with this vision, the global Sustainable Development Goal 4 (SDG 4) calls for inclusive and equitable quality education and promotes lifelong learning opportunities for all. A key target under this goal is the provision of safe, non-violent, inclusive, and effective learning environments, which includes the regular maintenance of infrastructure as a critical component of a functional education system. Together, these policies underscore the strategic importance of preventive maintenance not only for preserving infrastructure but also as an educational tool that reinforces practical learning, enhances safety, and supports the broader goals of national and international development agendas.

1.2. Statement of the Problem

Despite the presence of the 1977 maintenance policy, most institutions in Zambia suffer from neglected infrastructure, furniture and Surroundings. Maintenance is rarely incorporated into the

teaching process and is often reactionary and punitive. This disconnect hinders effective learning, wastes resources, and prevents the development of skills necessary for national development.

1.3.Objectives of the Study

This study aims to:

- 1.3.1.Develop context-responsive maintenance strategies for Zambian education institutions
- 1.3.2.Enhance human resource capacity through preventive maintenance literacy.
- 1.3.3.Promote sustainable infrastructure practices rooted in African knowledge systems.
- 1.3.4.Reposition PM as a pedagogical tool to instil resilience and responsibility in learners.

1.4.Study Population

The research was conducted in 10 government STEM Learning institutions in all the 10 Provinces of Zambia as well as the Directorate of National Science Centre.

1.5.Sample size

The study targeted a total of 15 participants comprising Heads of Departments (HODs), STEM subject teachers, and technical officers from the Directorate of the National Science Centre. These participants were selected due to their direct involvement in the planning, implementation, and maintenance of STEM-related infrastructure and learning programs

1.6.Sampling Technique

A purposive sampling technique was employed in this study. This method was chosen because it allowed the researcher to intentionally select participants who possess relevant knowledge, experience, and expertise in STEM education and preventive maintenance activities. This approach ensured the collection of in-depth and contextually rich data essential for the study's objectives.

1.7.Data Collection Methods

Data were collected using qualitative approach to ensure a comprehensive understanding of the study objectives. The following tools and methods were used:

- 1.7.1.Questionnaires: Structured questionnaires were administered to Heads of Departments and STEM teachers to gather quantitative data on their perceptions, practices, and challenges related to preventive maintenance in STEM learning environments.
- 1.7.2.Interviews: Semi-structured interviews were conducted with technical officers from the Directorate of the National Science Centre to obtain in-depth insights into the implementation and monitoring of maintenance programs in schools.
- 1.7.3.Observation Checklists: On-site observations were carried out in selected STEM institutions to assess the condition of infrastructure, laboratory equipment, and other learning facilities. This helped to validate information gathered through questionnaires and interviews.
- 1.7.4.Document Review: Relevant documents, including maintenance logs, monitoring reports, and policy guidelines, were reviewed to support and triangulate the data obtained from participants.

2. Literature Review

2.1. Literature Review: The Zambian Perspective

In Zambia, the issue of infrastructure maintenance in education has received minimal scholarly attention despite being a recurring challenge in government reports and sector reviews. While the 1977 maintenance policy introduced by the Ministry of Education provides a national framework for asset management, its application within the education sector has remained inconsistent and largely under-implemented. Most institutions operate on a reactive maintenance basis, often waiting for damage to escalate before repairs are made. This is partly due to budgetary constraints, lack of skilled personnel at the institution level, and the absence of structured preventive maintenance education in teacher training and STEM curricula (MOE, 1996; 2020).

The Ministry of Education's "Educating Our Future" (1996) policy document recognized the need for integrating maintenance into institutional operations, proposing that physical upkeep be seen as part of students' practical education. However, this recommendation has not been translated into actionable curriculum or programming in most schools. The Vision 2030 document further underscores the role of infrastructure quality in learning outcomes, noting that neglect of institutional assets diminishes learner safety and the overall educational experience.

Furthermore, institutional monitoring reports by the NSC (2023–2024) reveals that even newly installed laboratory workspaces deteriorate quickly due to improper use and lack of maintenance routines. This indicates a disconnect between infrastructure provision and sustainability planning. Some Learning institutions with proactive leadership have developed informal systems where Design and Technology students refurbish furniture or repair broken fixtures as part of coursework, but these are exceptions rather than the norm.

From a cultural perspective, Zambia's indigenous knowledge systems, particularly among Bemba, Tonga, and Lozi communities, have long emphasized communal responsibility for public infrastructure through practices such as *ukubokola* (communal cleaning or weeding) and *kusungilila* (caretaking). These practices can be repurposed within modern institutional management systems to foster a sense of ownership and sustainability. Yet, current institutional operations and policies rarely integrate these indigenous models into formal maintenance practices, despite their alignment with values such as environmental stewardship, care, and collective responsibility.

Overall, while Zambia has made policy-level commitments to infrastructure resilience and vocational education, there remains a significant gap in the integration of Preventive Maintenance into STEM education. Bridging this gap requires aligning national policies, indigenous knowledge, and curriculum design to create a new paradigm of education that is not only theoretical but also hands-on, locally relevant, and sustainable.

2.2. Operational measurements: PM compliance rate

The PM Compliance Rate serves as the cornerstone metric for evaluating the effectiveness of preventive maintenance (PM) practices in Zambian STEM educational institutions, quantifying the percentage of scheduled maintenance tasks completed on time within a single academic semester.

It is calculated using the formula:

$$\text{PM Compliance Rate (\%)} = \left(\frac{\# \text{ of PM Tasks Completed on Schedule}}{\text{Total \# of PM Tasks Due in Semester}} \right) \times 100$$

Figure 1 PM compliance formula

This indicator reflects institutional discipline, resource prioritization, and cultural commitment to shifting from reactive repairs to proactive asset care. In a context where the Ministry of Education’s 1977 maintenance policy and the 1996 *Educating Our Future* framework have long emphasized infrastructure upkeep but remain under-implemented due to budgetary limitations and skill gaps, achieving a $\geq 90\%$ compliance rate per semester emerges as a transformative target. This benchmark, aligned with international best practices and Zambia’s Vision 2030

goals, ensures laboratory reliability, enhances learner safety, and sustains the functionality of high-value STEM assets such as 3D printers, CNC machines, and fume hoods. Current NSC monitoring (2023–2024) reveals average compliance below 45% in supported schools, underscoring the urgency of this standard. Ultimately, a sustained $\geq 90\%$ PM compliance rate is not just a technical goal; it is a measurable pathway to transforming Zambia’s STEM learning environments into models of sustainability, ownership, and educational excellence.

3. Findings and Discussion

The study demonstrates that most learning institutions rely on reactive maintenance, which compromises both safety and infrastructure longevity. Integrating PM into STEM education not only improves facility reliability and hands-on learning opportunities but also fosters environmentally conscious practices. Although this study does not quantitatively measure climate outcomes, PM activities such as energy-efficient operation of electrical systems, timely repair of equipment, and sustainable management of furniture and waste imply a reduction in carbon emissions, resource consumption, and environmental degradation. For instance, repairing furniture and lab equipment extends their life, reducing demand for new materials and lowering the embedded environmental footprint. Similarly, maintaining green spaces and water systems conceptually promotes biodiversity and microclimate regulation. By embedding these practices into experiential learning, students develop environmental awareness and a culture of sustainability, creating an indirect pathway toward climate adaptation and mitigation. The findings suggest that systematically institutionalizing PM, in combination with teacher training, student engagement, and community partnerships, can simultaneously enhance STEM learning outcomes and encourage climate-conscious behaviour.

3.1. PM done on Infrastructure, furniture and surroundings

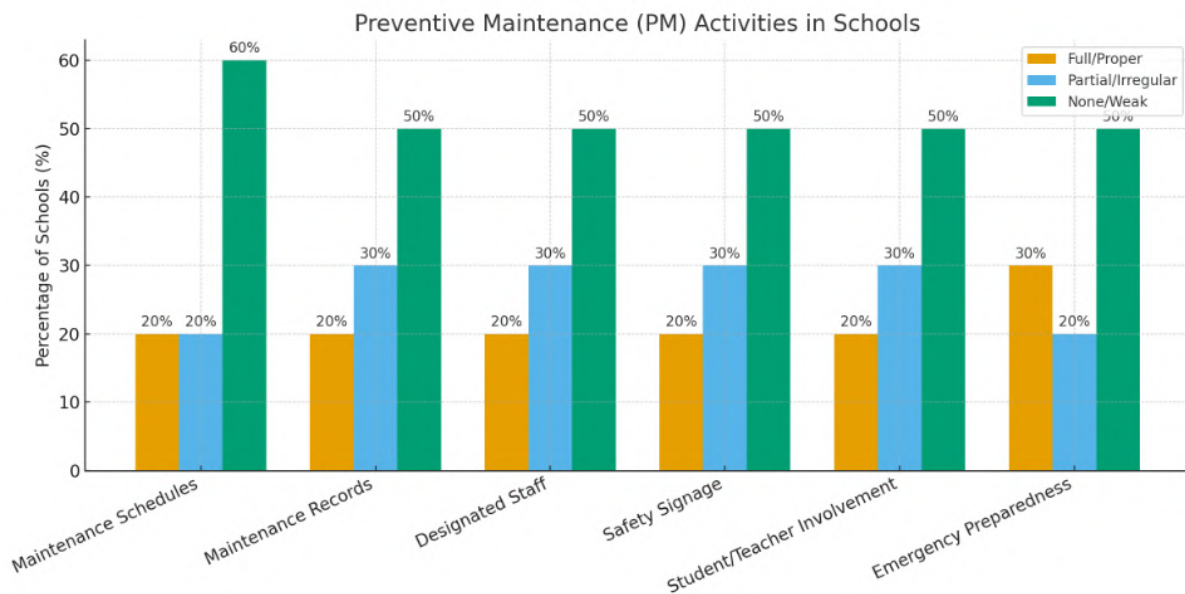


Figure 2 Findings on the PM on infrastructure, furniture and surroundings

The analysis of the graph on Preventive Maintenance (PM) activities in Learning institutions reveals critical gaps across all six measured components, underscoring the need for systematic and coordinated improvements. The findings show that preventive maintenance is poorly structured and inconsistently implemented in most schools. For example, only 20% of Learning institutions have established full and proper maintenance schedules, while another 20% apply them irregularly. A worrying 60% of Learning institutions have no maintenance schedules at all, highlighting weak planning systems for the upkeep of infrastructure and facilities. This lack of structured scheduling is likely to contribute to frequent breakdowns and higher long-term repair costs.

Maintenance records also present a significant challenge. Just 20% of Learning institutions keep comprehensive records, with 30% doing so partially. However, half of the Learning institutions (50%) do not keep any records, which means there is little accountability, monitoring, or institutional memory regarding maintenance activities. Without proper documentation, learning institutions are unable to track progress, identify recurring issues, or make informed decisions for resource allocation. Similarly, the designation of staff to handle PM activities is very low, with only 20% of Learning institutions having fully assigned personnel, 30% with irregular arrangements, and 50% with none at all. This demonstrates a lack of clear responsibility and accountability in managing maintenance, leaving facilities unattended and prone to deterioration.

Safety measures are also inadequate. Only 20% of Learning institutions have full safety signage in place, while 30% provide partial signage. Alarming, 50% of Learning institutions lack signage altogether, raising concerns about the safety of learners and staff in the event of hazards. The involvement of students and teachers in preventive maintenance is also minimal. Just 20% of Learning institutions engage them fully, while 30% involve them irregularly, and 50% show no involvement. This limited participation indicates weak awareness, lack of ownership, and minimal capacity-building in PM practices, all of which are vital for sustainability.

Emergency preparedness emerges as the relatively stronger component, with 30% of Learning institutions being fully prepared and 20% partially prepared. However, half of the Learning institutions (50%) still remain unprepared, exposing learners and staff to vulnerabilities in the face of emergencies such as fires, accidents, or natural disasters. While emergency preparedness is comparatively better, the fact that half of the Learning institutions are still unready suggests systemic weaknesses in risk management strategies.

Overall, the findings paint a concerning picture of preventive maintenance in schools. Across all six components, between 50% and 60% of Learning institutions fall under the “None/Weak” category, meaning that the majority lack proper systems, structures, or practices for PM. Very few Learning institutions (20–30%) demonstrate full and proper implementation of preventive maintenance. This shows that preventive maintenance is not yet prioritized as an essential part of school management. The absence of schedules, weak record keeping, lack of designated staff, poor safety signage, minimal involvement of learners and teachers, and inadequate emergency preparedness collectively point to significant risks of infrastructure deterioration, compromised safety, and limited resilience against emergencies. These findings highlight an urgent need for stronger policies, resource allocation, capacity building, and school-level accountability mechanisms to institutionalize preventive maintenance as a core function in the education system

3.2. PM activities observed

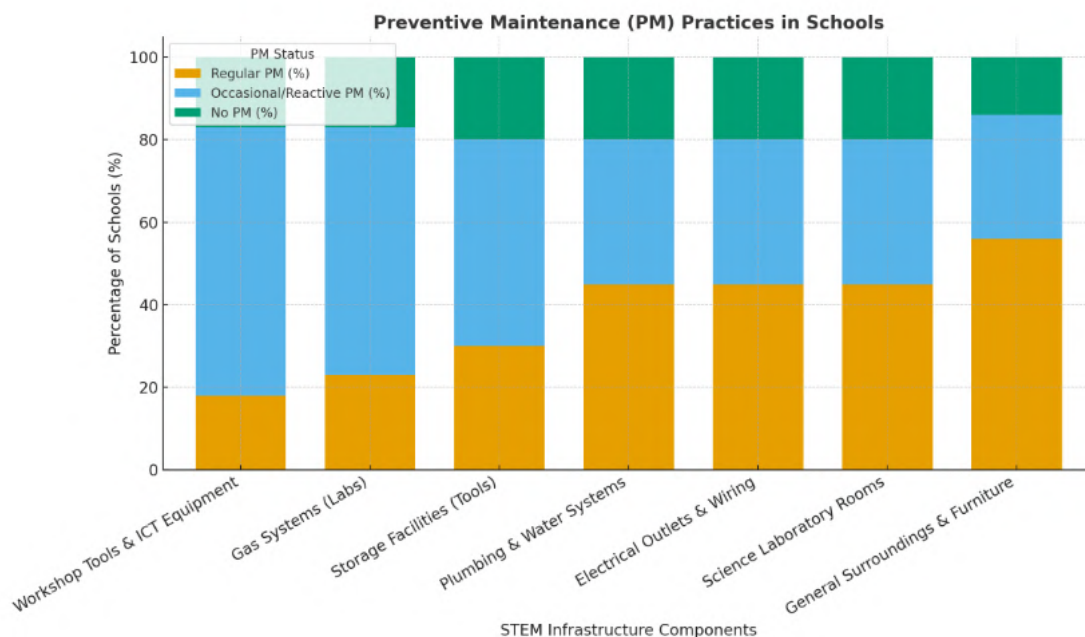


Figure 3 PM activities observed

The graph on Preventive Maintenance (PM) Practices in Learning institutions as shown in Figure 3. illustrates how Learning institutions are managing different STEM infrastructure components, showing three levels of maintenance: Regular PM, Occasional/Reactive PM, and No PM. The findings reveal significant variations across components, with a general trend of more reliance on reactive or occasional maintenance than on structured, regular PM. For Workshop Tools and ICT Equipment, only about 20% of Learning institutions conduct regular preventive maintenance, while the majority, around 65%, rely on occasional or reactive maintenance. About 15% of Learning

institutions provide no PM at all, which exposes equipment to risks of frequent breakdowns. In Gas Systems (Labs), regular PM is even lower, at about 20–25%, with most Learning institutions (around 60%) carrying out occasional/reactive maintenance, and nearly 20% not conducting any maintenance. This is a major safety concern, as gas systems are high-risk components that require consistent monitoring.

Storage Facilities (Tools) present a slightly better picture, with approximately 30% of Learning institutions practicing regular PM and 50% depending on occasional/reactive PM. Still, about 20% of Learning institutions carry out no maintenance, risking deterioration of learning materials. For Plumbing and Water Systems, regular PM rises to about 45%, with 40% doing occasional/reactive maintenance and about 15% having no maintenance at all. This shows progress but still highlights gaps in ensuring reliable water and sanitation facilities. In the case of Electrical Outlets and Wiring, only about 45% of Learning institutions conduct regular PM, while 40% rely on reactive measures and 15% provide no PM. Considering the safety hazards posed by faulty electrical systems, this gap is significant. Similarly, for Science Laboratory Rooms, around 45% of Learning institutions perform regular PM, 35% carry out reactive maintenance, and 20% do none, suggesting that laboratory safety and functionality are at risk.

The General Surroundings and Furniture show the highest level of regular PM, at about 55%. Another 30% rely on occasional/reactive PM, while about 15% conduct no maintenance. Although this area appears relatively better maintained compared to others, the 15% gap still indicates neglect in maintaining the overall learning environment. Overall, the findings demonstrate that most Learning institutions rely heavily on occasional or reactive maintenance across all STEM infrastructure components, with only 20–55% consistently conducting regular preventive maintenance. Between 15% and 20% of Learning institutions do not perform any maintenance at all, especially in critical areas like gas systems, electrical wiring, and laboratory rooms, which poses safety and operational risks. The data underscores the urgent need to strengthen preventive maintenance culture in Learning institutions by prioritizing structured schedules, assigning responsibilities, and ensuring adequate resources to safeguard infrastructure, improve safety, and extend the lifespan of STEM facilities.

3.3. General Preventive Maintenance

The analysis of general Preventive Maintenance (PM) practices in STEM schools, based on a structured set of questions, reveals a blend of proactive initiatives, resource limitations, and institutional gaps. STEM Learning institutions sampled define PM as a routine or proactive effort to preserve equipment, infrastructure, and learning environments, focusing on reducing wear and tear, minimizing equipment failure, and promoting safety. In this context, PM is recognized as essential to ensuring uninterrupted learning, enhancing student safety, and supporting innovation through hands-on learning. However, the depth of understanding and prioritization of PM varies significantly across schools. Learning institutions generally acknowledge the importance of PM, citing its role in extending the lifespan of tools and equipment, reducing costs, and providing safe, functional learning spaces. Some Learning institutions note that it helps facilitate creative and practical learning experiences vital in STEM education. Despite this awareness, the implementation of PM systems varies. While a few Learning institutions have established formal committees or clubs dedicated to PM—sometimes even included in school timetables, others rely solely on general school-wide schedules or address maintenance only when issues arise.

Responsibility for PM is typically assigned to a combination of stakeholders, including heads of departments, designated caretakers, teachers, and in some cases, prefects. In several cases, D&T teachers are mentioned as key drivers of maintenance, often working with learners, particularly in repairing damaged furniture and tools. In others, the deputy headteacher or science department representatives oversee PM routines. Notably, most Learning institutions engage both teachers and learners in PM activities, with roles ranging from cleaning to hands-on repair work. This involvement is seen as an opportunity to build responsibility, teamwork, and technical competencies such as carpentry, metal fabrication, plumbing, and basic electrical maintenance. Despite these efforts, numerous challenges hinder effective implementation. Chief among them are financial constraints, which limit the acquisition of tools, equipment, and materials necessary for meaningful PM. Human resource shortages are also noted in a few cases, although some Learning institutions report having adequate staff but lack the technical knowledge or equipment to perform maintenance effectively. Other challenges include inadequate cooperation among teachers, lack of proper supervision, and limited awareness or training on how PM should be conducted.

The consequences of poor maintenance are significant. Learning institutions report disruptions to teaching and learning due to faulty tools, dirty environments, or unsafe conditions. Examples include learners being injured by damaged tools or chemical spills resulting from poorly stored materials. Malfunctioning or insufficient equipment also limits hands-on learning opportunities, leading to reduced engagement and compromised skill development. When asked about national guidelines on PM, most respondents were either unsure or reported that such guidelines were lacking or unclear. Consequently, many Learning institutions operate without standardized procedures, leaving PM to the discretion of individual Learning institutions or departments. To improve this situation, learning institutions recommend increased funding, training, clearer guidelines, regular inspections, the establishment of dedicated maintenance plans, and the appointment of qualified caretakers with relevant trade skills. Finally, involving learners in PM is widely regarded as beneficial. Educators believe it promotes technical skill development, critical thinking, teamwork, and a sense of ownership over school resources. Such engagement not only supports the goals of STEM education but also contributes to developing problem-solving abilities and lifelong practical skills. While the importance of PM is well recognized across STEM schools, the practice is uneven due to financial, technical, and systemic constraints. Strengthening PM in Learning institutions will require coordinated policy support, stakeholder involvement, and investment in infrastructure, training, and equipment.

4. Proposed Concept note for Integrating PM into STEM Education

To effectively integrate Preventive Maintenance (PM) into STEM education, a comprehensive concept is proposed that blends curriculum reform, capacity building, practical engagement, community collaboration, and policy reinforcement. The first component involves curriculum integration, where PM topics are deliberately introduced into existing subjects such as Design and Technology (D&T) and Integrated Sciences. This would ensure that learners acquire both theoretical knowledge and practical understanding of infrastructure care, sustainability, and technical responsibility as part of their everyday learning experience. Secondly, the concept emphasizes the importance of teacher training through targeted in-service programs and professional orientation workshops that equip educators with the skills and knowledge to incorporate maintenance principles into lesson delivery.

Teachers would also be trained in using institution infrastructure as a learning resource, promoting a culture of care and responsibility among learners.

Thirdly, the concept advocates for practical learning projects that actively involve learners in real-world maintenance tasks. These could include activities such as refurbishing broken furniture, maintaining science laboratory equipment, or keeping institution gardens and water systems. Such projects would reinforce the link between STEM concepts and everyday problem-solving, while also fostering a sense of ownership and discipline among students.



Figure 4 Learners participating in Preventing Maintenance at a learning institution



Another key aspect is the introduction of monitoring tools, including maintenance checklists,

logbooks, and digital tracking systems, to ensure routine PM tasks are systematically recorded and evaluated. These tools would also help Learning institutions assess the condition of STEM facilities and make informed decisions regarding repairs and upgrades. Community involvement forms a critical pillar of this model. Learning institutions would actively partner with Parent-Teacher Associations (PTAs), local artisans, and community elders who possess traditional knowledge and technical skills. These partnerships would provide mentorship for learners, strengthen local ownership of institution resources, and promote indigenous maintenance practices that are sustainable and cost-effective.



Figure 5 Learners participating in JETS Competitions as a form of PM in learning institutions

The concept calls for policy

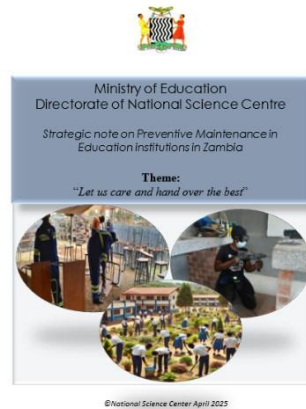


reinforcement by revisiting and updating the 1977 Education Reforms to place greater emphasis on infrastructure education, environmental sustainability, and skill development. This policy shift would institutionalize PM within the national education framework and align Zambia's educational objectives with global sustainability goals, including SDG 4 and Agenda 2063. Together, these strategies provide a holistic approach to embedding preventive maintenance into STEM education—

enhancing not only the longevity of institution infrastructure but also the technical competence, responsibility, and sustainability consciousness of future generations.

Figure 6 Strategic note on preventive maintenance for Zambian Learning institutions

5.Preventive Maintenance as a Climate Solution



Preventive maintenance is increasingly recognized as a climate adaptation and mitigation strategy across multiple sectors. In infrastructure, regular inspections and timely repairs reduce energy consumption, prevent efficiency losses, and minimize greenhouse gas emissions associated with building degradation (IPCC, 2022). Maintaining roofs, gutters, insulation, electrical systems, and ventilation prevent resource waste and prolongs the service life of school facilities, thus reducing the carbon footprint associated with new construction. In surrounding environments, PM supports the sustainability of green spaces, tree belts, and school gardens, which purify air, mitigate urban heat island effects, and promote biodiversity. Likewise, proper maintenance of waste management systems, including recycling centers and composting spaces, reduces pollution and methane emissions from landfills.

Furthermore, PM applied to school furniture supports sustainable production and circular economies. By repairing, repurposing, and maintaining desks, chairs, and laboratory benches, schools reduce deforestation and limit the demand for resource-intensive new furniture (FAO, 2021). Instead of discarding damaged items, PM encourages restoration, reducing solid waste and promoting responsible consumption, in line with SDG 12. Incorporating PM practices into daily school operations ensures that institutions play an active role in climate action, resource conservation, and environmental education.

6. Proposed Model for Preventive Maintenance implementation

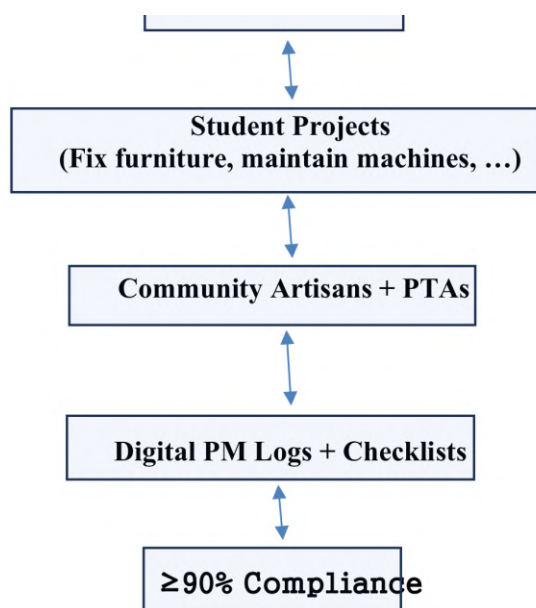


Table 1 Proposed model for PM Implementation

The proposed model for integrating Preventive Maintenance (PM) into STEM education is designed as a holistic, multi-stakeholder framework that links curriculum reform, teacher capacity-building, community involvement, and digital monitoring systems to improve infrastructure resilience in Zambian learning institutions. At its foundation, the model embeds PM concepts directly into the Design and Technology (D&T) and Science curriculum through structured modules that teach learners the principles of inspection, diagnosis, repair, and sustainability-based maintenance. This curricular anchoring ensures that PM is not treated as an ad-hoc activity but as a formalised learning outcome aligned with competence-based education and national development frameworks.

To support curriculum delivery, the model includes teacher training as a core component, recognising that effective implementation depends on the teacher's ability to translate PM concepts into practical, learner-centred activities. Teachers are therefore equipped with technical and pedagogical skills for guiding maintenance tasks, supervising hands-on work, and integrating indigenous African knowledge systems in line with Zambia's education policies. These trained educators subsequently facilitate student-led PM projects, which form the experiential learning element of the model. Projects may include repairing school furniture, maintaining workshop machines, servicing laboratory equipment, and managing classroom environments. This approach reinforces technical competence, problem-solving, responsibility, and a culture of stewardship. A unique feature of the model is the deliberate inclusion of community artisans and Parent–Teacher Associations (PTAs). Local artisans bring contextual expertise in carpentry, metalwork, electrical systems, or masonry, fostering school–community partnerships and linking PM learning to local economies. PTAs provide governance support, resource mobilisation, and oversight, ensuring that PM activities become routine and sustainable rather than episodic. This integration strengthens community ownership of school infrastructure and aligns with African communal value systems that emphasise collective responsibility.

To ensure monitoring, accountability, and data-driven decision-making, the model incorporates digital PM logs and checklists. These tools are used to track scheduled maintenance tasks, record

completion dates, monitor compliance, and generate reports for school leaders, district offices, and national directorates. Digitalisation helps reduce information loss, supports real-time tracking, and creates a structured maintenance culture. According to the model, a PM task is considered compliant only when it is undertaken on or before the scheduled due date, and the minimum acceptable performance for schools is a $\geq 90\%$ PM compliance rate.

When all components work together; curriculum modules, trained teachers, student projects, community support structures, and digital monitoring, they reinforce one another and create a comprehensive system for embedding preventive maintenance in STEM education. The expected outcome is a generation of learners who are skilled, responsible, environmentally conscious, and capable of sustaining school infrastructure, while supporting national goals in sustainability, climate resilience, and human capital development.

7. Conclusion

Preventive Maintenance (PM), when meaningfully integrated into STEM education, offers a multifaceted solution that goes beyond addressing physical infrastructure challenges in schools. It becomes a transformative educational strategy that enhances the quality of learning by fostering a practical, hands-on approach to STEM. By incorporating PM into the curriculum, learners are given the opportunity to apply theoretical knowledge in real-world contexts, thereby bridging the gap between classroom learning and everyday life. This experiential learning not only deepens understanding but also cultivates vital skills such as critical thinking, problem-solving, teamwork, and innovation. Moreover, engaging students in the care and upkeep of their learning environments instils a sense of ownership, responsibility, and civic duty. It encourages them to see themselves not just as consumers of education, but as contributors to the sustainability and functionality of their schools. In doing so, the integration of PM aligns naturally with indigenous African systems of care, communal responsibility, and environmental stewardship, which have long emphasized the value of maintaining shared resources for the benefit of all. Strategically, this integration supports key national and international policy frameworks. It directly aligns with Zambia's Vision 2030, which emphasizes quality education and lifelong learning as pillars of national development. It reinforces Sustainable Development Goal 4 (SDG 4) by contributing to the creation of safe, inclusive, and effective learning environments. Additionally, it echoes the aspirations of Agenda 2063 by promoting a skills revolution and self-reliance among African youth, and it is well-anchored in the Eighth National Development Plan (8NDP), which highlights the importance of skills development, sustainability, and innovation in education. Ultimately, embedding preventive maintenance into STEM education repositions learners as active agents in preserving national resources. It prepares a new generation that is not only academically competent but also practically skilled, environmentally conscious, and socially responsible. This approach ensures that the country's investments in educational infrastructure and human capital are protected and sustained, laying a solid foundation for long-term national progress and resilience.

8. Recommendations

8.1. Schools should adopt clear, routine maintenance plans covering all critical infrastructure and STEM tools, embedding energy-efficient practices and resource-conscious habits.

8.2. There should be a way to ring-fence funds for PM, including tools, replacement parts, and

safety inspections that indirectly reduce environmental impact by preventing premature replacements and waste.

8.3. Standardized practices should promote sustainable material use, repair-based culture, and energy-efficient routines, acknowledging the climate co-benefits of effective maintenance.

8.4. Training for staff and students should include awareness of environmental stewardship, demonstrating how PM practices can indirectly mitigate climate risks and resource wastage.

8.5. Involving learners in PM reinforces ownership, technical skills, and sustainability literacy, fostering habits that support climate-resilient thinking.

8.6. Use digital logs and checklists to track not only PM compliance but also encourage practices that reduce resource consumption, minimize waste, and extend equipment life.

8.7. Engage PTAs, artisans, and local elders to integrate indigenous, sustainable practices into PM activities, promoting low-carbon and locally adapted solutions.

8.8. Emphasize the dual benefits of PM for infrastructure resilience and environmental sustainability, clarifying that climate impact is conceptual and qualitative, guiding future empirical studies.

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ARTICLE 4

STEM Pathway In Senior Schools; Developing Communication and Collaboration skills by learners in their STEM projects.

Peter M. Ndiritu

pevalinx@gmail.com

Mt Kinangop Girls Secondary School, Kenya

ABSTRACT

STEM pathway can prepare learners for the challenges of the 21st century living by ensuring that they have effective competencies. One of these competencies is communication skills. Communication can occur either in written or oral form. In most cases, learners are not able to communicate effectively in both forms. The research question dealt on how communication skills affect learners' performance in their STEM projects by comparing their written & oral communication skills, scientific thoughts, methods and creativity in expressing their learning outcomes. The data collected comprised of 4 STEM subjects categories, i.e. chemistry, biology, mathematics and physics with a total of 15 projects per category. Written communication, part A, of the project was scored separately from oral communication, part BC. These two parts were treated as dependent variables against the total number of projects per category. On a scatter plot with a smooth line, both dependent variables produced converging and diverging curve areas while when both parts scores were added up and plotted against the total number of projects per category, a gradual declining line graph was produced. Written communication demands a lot of time and effort for thinking and reflecting on the area of study, while in oral communication factors such as anxiety, lack of confidence & limited practicing opportunities can impede development of these skills. Therefore, there is need for learners to develop more of their written & oral communications skills in order to convey their learning outcomes effectively.

Keywords: Learning outcomes, communication skills, competencies, STEM pathway, Projects.

List of abbreviation

CBE: Competency base education.

CEMASTE: Centre for Mathematics Science and Technology Education in Africa. KSEF: Kenya Science and Engineering Fair.

STEM: Science, Technology, Engineering and Mathematics.

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1.0 Introduction

There is a greater need, in Africa, for science, technology, engineering, and mathematics (STEM) education in order to prepare for current and future economic needs and a workforce that can navigate through the challenges of the 21st century living (Chou, 2018). Therefore students in the 21st century must be able to think critically and be able to solve the problems, be creative and innovative, to be able to collaborate and communicate effectively (Barus & Sahur, 2024; Erdogan, 2019; & Puji, et al 2019). In order to communicate and collaborate effectively in STEM education, the paradigm has changed emphasizing on creation of new knowledge and its innovative application (Somphol, et al 2022). In order to create new knowledge, the learners should be able to actively, acquire and synthesize new information, building on prior knowledge, by analyzing it, evaluating evidence and learning outcomes demonstrated through their innovativeness.

Information synthesis in the process of analyzing information and evaluating evidence from various sources, making connections of the facts gathered, and thus, building the acquired new information on the prior knowledge to become effective in communication (Diekema, et al 2025). Therefore, the learners should be able to collaborate and communicate effectively in written and oral communication, scientific thoughts, methods and creativity in order to create new knowledge for novelty innovations.

1.1 Inter-disciplinary teaching and learning

STEM education is a pedagogical approach that integrates inter-disciplinary teaching and learning which fosters development of multiple skills. Its over-arching objective is to cultivate workforce who possess the capacity to devise innovative solutions but synthesizing new information through analyzing it and evaluating evidence for knowledge acquisition from diverse fields in STEM (Golegou, et al, 2025).

Inter-disciplinary teaching and learning in STEM education differs from the traditional, teacher-centered, education system. It involves holistic teaching and learning which nurtures knowledge, skills, values, attitude and learning outcomes (Kanmaz, 2022). Learning outcomes refers to what a learner should know (knowledge acquisition) and be able to do (knowledge application), leading to skills development for competencies as a result of learning experience. In its space, learning is active and student-centered. It provides hands-on learning experiences where by the depth of understanding is often retained for a longer period since the learners take the lead in applying knowledge learnt, enforcing cognitive development for competencies (Ndiritu, 2023).

But, in the traditional education system, learning is passive and individualized where learners compete for grades and recognition rather than working collaboratively (Divya, 2025). Additionally, it encourages rote learning, with the teacher at the center of learning. Since inter-disciplinary learning promotes inquiry minds, logical thinking and collaboration (Birzina, 2023), the approach provides the learners with the opportunity to work relatively autonomously (John, 2000) to increase their engagement (Shukla, et al 2024)

When learners work autonomously or independently for an emergent learning context, they become more engaged, motivated and academically successful (Hennessey, 2021). This is because, it helps

them to connect academic concepts and principles into tangible outcomes by translating abstract concepts to concrete examples making learning experience meaningful and exciting.

Therefore, inter-disciplinary teaching and learning approach to STEM education transform learners into critical thinkers who can engage with and in turn help create new knowledge. The approach provides students with a sense of purpose, equip them with prior knowledge to build upon the new knowledge they gain or gather. Wami (2024) argues that the approach can be a catalyst to learners' development of critical thinking and problem solving skills. This helps them to create new knowledge as they are able to synthesize new information by analyzing and evaluating evidence objectively and rationally allowing individuals to make informed decisions and solve problems effectively through creativity.

1.2 Statement of the problem

Acquiring new knowledge is a process that is constructed through communication marked by research and critical reflection (Zabrano, et al 2022). Communication skills are important in learning STEM as they involve transfer of information in ways that permit those who receive it to interpret and act upon it in ways intended. Communication occurs in written or oral form. In most cases learners are not able to communicate effectively in both forms. They tend to be effective in one form and less effective in the other. Written communication skills involves cognition, brainstorming, planning, outlining, organizing, drafting & revising, thus demanding a lot of time and effort for thinking and reflecting on the area of study. In oral communication, factors such as anxiety, lack of confidence & limited practicing opportunities can impede these skills development. Therefore, there is need for learners to develop more of their written & oral communication skills so that they can effectively display their learning outcomes

1.3 Objective

To compare the learning outcomes of learners in their collaborative written & oral communication, scientific thoughts, methods and creativity, and their effects in STEM projects performance.

1.4 Research question

How do communication and collaborative skills affect learners' performance in STEM projects competitions?

2.0 Literature review

2.1 STEM Pathway

One of the pathways in Competency Based Education (CBE), in Kenya, is STEM pathway. Critical thinking and problem solving, creativity and imagination, communication and collaboration among others are key components of competencies in CBE (Muchira, et al, 2023). Communication skills enable learners to articulate ideas effectively, collaboratively and build confidence leading to improved academic outcomes. For effective communication, learners must have prior knowledge to build upon in the process of acquiring new knowledge.

2.2 Knowledge Acquisition

In order to acquire new knowledge for new ideas and concepts, prior knowledge is essential as it lays foundation for learning new concepts (Mabonga, 2021). Knowledge arises through a process of active construction which implies that prior knowledge cannot be transmitted from one person to another, rather, it is constructed through active learning process. Thus, learners build upon what they already know, and from that, they build upon by reconstructing their prior knowledge as they learn from their past and integrate their present learning experience (Diaz, 2017). Acquiring of new knowledge is constructed through communication marked by research and critical reflection (Zabrano, et al 2022)

For learners to integrate their past learning with new concept, they must acquire new knowledge. According to Kaba (2019), knowledge acquisition is the process of extracting, structuring and organizing new information from one or more sources into meaningful form. This involves actively engaging with the new information, structuring it and storing it in a way that allows for future recall and use with a focus of expanding and integrating it with existing knowledge.

Since inter-disciplinary teaching and learning in STEM education promotes autonomy of learners, it gives them independence of learning. When learners acquire knowledge through their own effort, they develop their ability to inquiry and logical thinking as it places increased learning responsibilities on them (Vijay, 2024). This helps them to make sense of why the acquired knowledge is useful and how it might be applied (Oleg, et al 2016)

2.3 Knowledge Application

Knowledge application is the link that connects what we know with what we don't. It's the process of using theoretical concepts, learnt skills or information and effectively applying them in problems solving by transforming insight into action (Anderson, 2024). In academic setting, students apply their learning through discussions, exams and projects. This helps in reinforcing their understanding and enhancing retention.

STEM education emphasizes on active, hands on learning experience that empower students to tackle real world challenges. This approach diverges from the conventional teacher- centered learning, thus creating a dynamic education learning space. This allows the learners to delve into acquired scientific principles into tangible ways, with evidence, by leveraging them into practical scenarios, thus bridging the gap between abstract knowledge and practical knowledge application (Nadia et al, 2024), thus demonstrating skills acquired (Besa,2022).

2.4 Literature gap

Written communication skills involves cognition, brainstorming, planning, outlining, organizing, drafting & revising, thus demanding a lot of time and effort for thinking and reflecting on the area of study. In oral communication and collaboration, factors such as anxiety, lack of confidence & limited practicing opportunities can impede these skills development.

Learners have to be effective in their communication skills to effectively convey their learning outcomes, both in written and oral communication, scientific thoughts, methods and creativity, in order to create new knowledge for novelty innovations. It is important to improve learners' communication and collaborative skills in order for them to appropriately convey their learning outcomes (Octavia, 2022). This in turn will help the learners to effectively demonstrate acquired knowledge and

competencies through their creativity and self-expression (Rahman, 2024), thus leading to knowledge creation for new innovations. With this ability to synthesize complex information for knowledge acquisition, into constructive applications through creativity, the learners are able to contribute to the development of knowledge, communicated both in written and orally, for local community & the nation at large. This promotes their citizenship which is one of the core competencies in CBE curriculum.

3.0 Methodology 3.1 Research design.

The data used was obtained from the ministry of education, Nyandarua County.

The selected sample of male and female student participants were from public and private secondary schools affiliated to the ministry of education, Nyandarua County, and they had participated in 2025 Kenya Science and Engineering Fair (KSEF) competitions at the county level. In the 4 project categories involved, the presenters were in pairs from 15 different schools sampled randomly out of 24 schools that participated per project category. This made up a total of 30 participants comprising of 15 boys and 15 girls. Out of 15 schools sampled per category, 5 were purely girls schools, 5 purely boys schools and 5 mixed schools, comprising of national, extra-county, county and day schools.

3.2 Data collection

This research was carried out by collecting data of 4 project categories, related to STEM learning, out of the 13 categories presented in KSEF 2025 competitions. The four categories included; Biology, Chemistry, Physics and Mathematical science. The data collected from each project comprised of part A, part BC. Part A data consisted of written communication with a maximum of 30 marks, while part BC consisted of oral communication, scientific thoughts, methods and creativity with a maximum of 50 marks. Both part A and BC marks were used as dependent variables while the total number of projects per category was used as independent variables for graphical representation.

3.3 Data collected

N O	CHEMISTRY PROJECTS			BIOLOGY PROJECTS			MATHEMATICS PROJECTS			PHYSICS PROJECTS		
	PART A /30		TOTAL /80	PART A /30		TOTAL /80	PART A /30		TOTAL /80	PART A /30		TOTAL /80
1	24	41	65	24.75	40	64.8	23	36	59	28.5	44	72.5
2	24.75	39.5	64.3	18	40.5	58.5	24	34.5	58.5	28	44.5	72.5
3	25.5	37.5	63	23.5	33.5	57	24.75	32.5	57.3	27	41	68
4	24.25	34	58.3	21.5	34.5	56	23.5	33	56.5	25	40.5	65.5
5	26.75	31.5	58.3	21.5	34	55.5	20.5	33	53.5	21	41	62
6	24	34	58	22.5	32.5	55	23.5	28	51.5	26.5	34.5	61
7	17.25	35	52.3	23.75	31	54.8	22.25	25.5	47.8	20.5	38.5	59
8	21.25	30.5	51.8	18	36	54	20.75	26	46.8	19.75	35.5	55.25
9	15.5	34.5	50	18.5	35	53.5	21.5	25.5	47	23.75	32	55.75
10	18.25	31	49.3	22	31	53	20	26	46	12	43.5	55.5
11	19.5	29.5	49	17.75	30	47.8	17.75	27.5	45.3	19.25	35.5	54.75
12	17.25	29	46.3	19	27.5	46.5	23	22.5	45.5	18	34.5	52.5
13	19.5	25.5	45	20.75	24	44.8	16.5	27.5	44	15	36.5	51.5
14	12	29.5	41.5	16.5	25	41.5	18	24	42	16.5	29	45.5
15	16.5	23.5	40	16.5	23	39.5	15.5	20.5	36	13.5	27	40.5

Table 3.0 Project categories scores in part A, written communication, & part BC, oral communication, Scientific thoughts, methods, and creativity and totals of part A plus BC.

4.0 Data analysis

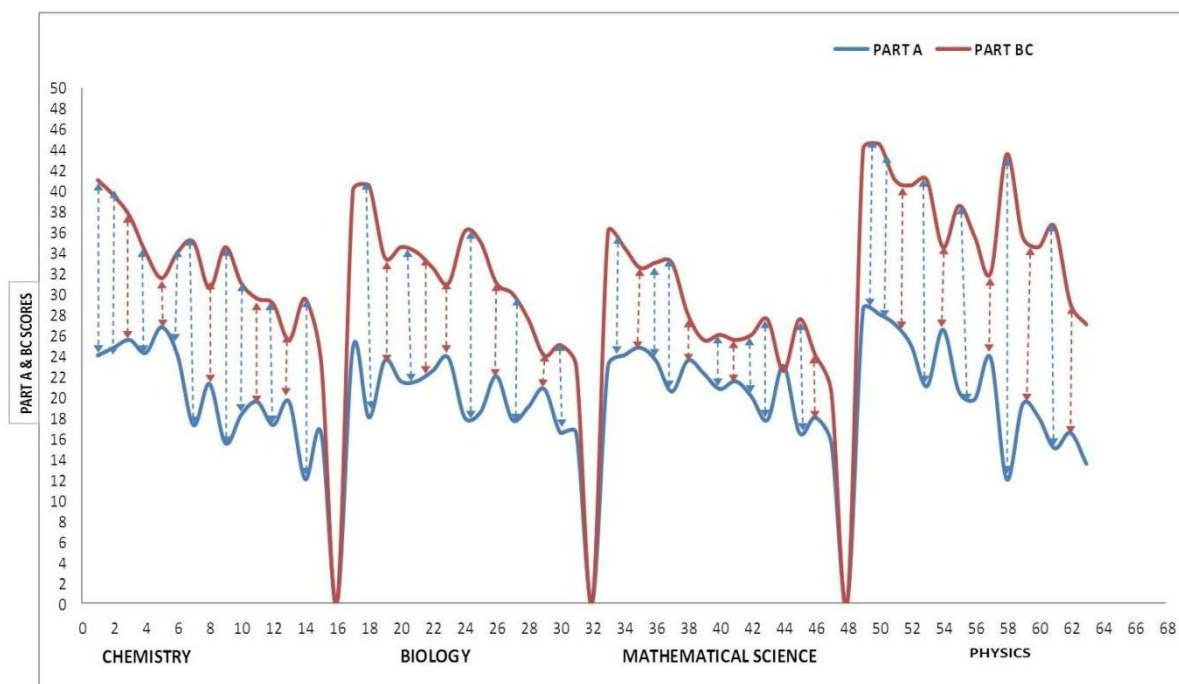


Figure 4.0: A scatter with smooth line graphs of part A & part BC scores against total number of projects per category.

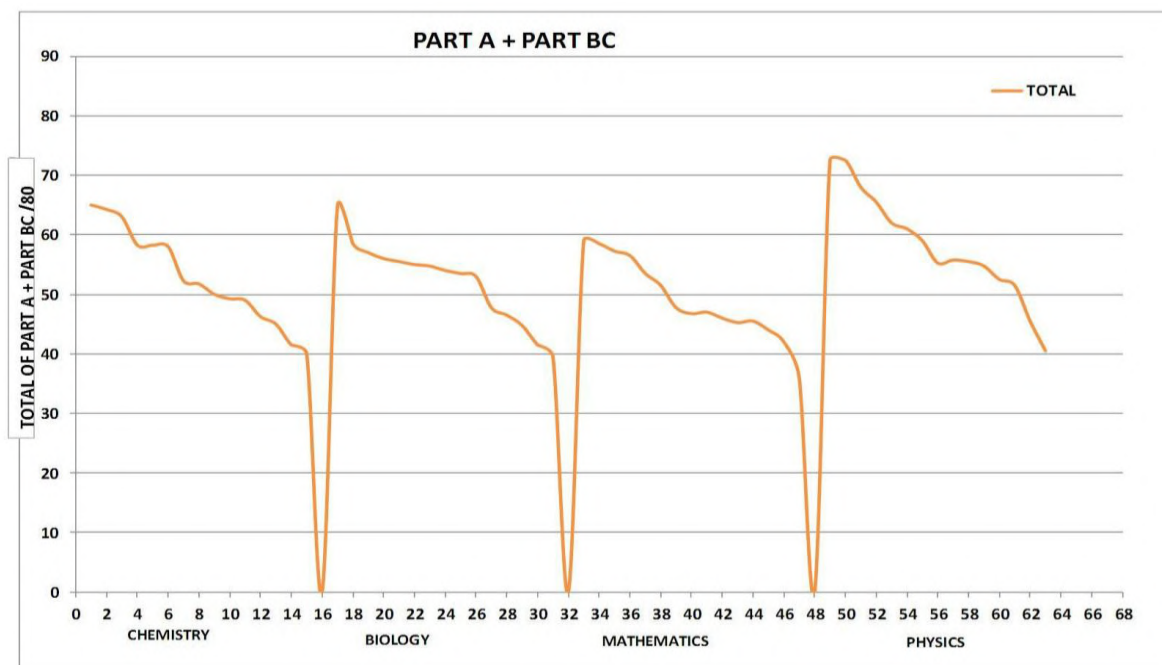


Figure 4.1: A scatter with smooth line graphs of totals of part A plus part BC scores against total number of projects per category

4.1 Findings

In the four project categories involved, that is, chemistry, biology, mathematics & physics, the marking schemes used in judging the projects were divided into two parts, part A and part BC which were

scored independently. Part A comprised of written communication while part BC comprised of oral communication, scientific thoughts, methods and creativity. Both part A and part BC were used as dependent variables while the number of projects per category was used as independent variable. The totals of both part A plus part BC were used to rank the projects performance per category.

When dependent variables were plotted against independent variables, in scatter with smooth line graph against the total number of projects as an independent variable, per category, both dependent variables produced diverging and converging zones to each other. On the diverging zones, the project presenters' scores were high in oral communication, scientific thoughts, methods and creativity with low scores in written communication and vice versa in converging zones. When the total scores of part A plus part BC were plotted in scatter with smooth line graph against the total number of projects, a gradual declining line graph was produced.

When learners were carrying out their scientific projects, written and oral communication, scientific thoughts, methods and creativity were necessary skills to develop quality projects. Learners who possessed these skills scored highly in their project, thus having better chances of proceeding to the next level of competitions. If learners had high skills, both in part A and part BC, with gradual decline line graphs of dependent variables would be produced without convergent and divergent zones.

Communication skills are important in learning STEM (Fatiha et al, 2022), as it involves transfer of information in ways that permits those who receive it to interpret and act upon it in ways intended (Byakutanga, 2016). Communication can occur in written or oral form.

Written communication is considered a critical student learning outcome (Alarcon et al, 2024), as it focuses on learning activities that allow students to transit gradually from knowledge acquisition to knowledge transformation, where there is a dynamic interaction between the students with essential writing skills and reflective process (Herdan, 2021). Writing involves cognition, brainstorming, planning, outlining, organizing, drafting and revising and it demands a lot of time for thinking and reflection on topic (Vysotska, 2022). Therefore, competency in written communication develops critical thinking skills as it demands analysis of the information and its evaluation and requires effort by students to write well since it cannot be acquired naturally (Riaz & Gul, 2016).

On the other hand, oral communication is a skill that enables students to engage in dialogue within diverse discursive practices, thereby fostering social participation as it involves both speaking and listening (Benavides et al, 2025). According to Rahman (2024), research has shown that factors such as anxiety, lack of confidence and limited practicing opportunities can impede development of oral communication. But, Apart et al (2023) argues that students with high level of oral communication skills can effectively express their scientific thoughts, ideas, engage in meaningful conversations and articulate their viewpoints confidently with clarity.

5.0 Conclusion

Effective communication and collaboration help learners acquire and apply knowledge by being critical on the information from various sources and making connections. With proper communication, learners are able to have an objective analysis of information and evaluation of evidence in order to come to a conclusion. This helps to solve problems by finding solutions to difficult or complex issues.

In order to solve these problems, the learners have to be creative and imaginative in order to be able to come up with new ideas to create novelty leading to innovations and knowledge creation. With this ability to creativity, the learners are able to contribute to the development of knowledge for local community and the nation at large. This promotes their citizenship which is one of the core competencies in CBE curriculum.

5.1 Recommendation

Learners should be encouraged to participate in symposium, conferences and podcasts to present STEM projects and ideas. To enhance practice, there should be professional development of teachers on pedagogical approaches that nurture communication & collaboration among learners such as project based learning. Therefore, there is need for implementation of action research & lesson study at school level and clusters through formation of community of practice in STEM education.

In terms of policy, there is need for increasing funding to enhance quality and quantity of infrastructure in schools necessary for supporting STEM education, in particular STEM pathway in senior schools.

5.2 Acknowledgment

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ARTICLE 5

From Recall to Real: Transforming STEM Education Assessment in Africa through Competence-Based Learning

Benson Banda 1, Emanuel Omang Ocquaye 2,
Ndege Samuel³, Debra Mwango 4

¹bensonbanda2003@yahoo.co.uk, ²emmanuelocquaye@gmail.com, ³ndegesam1@gmail.com,
⁴deborah.mwango@yahoo.com

^{1,4} Ministry of Education, Directorate of National Science Centre, ² Ghana Education Service Science Unit, ³ St. Mary's High School-Lushangonyi

ABSTRACT

African education systems are shifting from Outcome-Based Curriculum (OBC) to Competence-Based Curriculum (CBC), anchored in constructivist and authentic learning paradigms, to emphasize what learners can do rather than what they can recall. Yet assessment practice has lagged behind curriculum policy. This study analyses multi-country qualitative data from 392 WhatsApp posts by 52 educators from the AfriSTEM WhatsApp discussion, held from 5 to 10 October 2025, and facilitated by the Directorate of Zambia's National Science Centre. Educators from ten African countries debated how assessment must change to reflect competence development. Thematic analysis revealed three domains of transformation: (1) redefining assessment purpose—learning and empowerment rather than sorting; (2) redesigning assessment tasks—authentic tasks in real or realistic contexts measuring knowledge, skills, and values; and (3) reconfiguring systems—policy reform, teacher professional development, and moderation for trust. Recommendations include elevating formative assessment, integrating indigenous knowledge, and developing an African-owned continental framework (CAF-Africa), a proposed policy model for harmonizing competence assessment across African states. Findings suggest that the sustainability of African STEM education reforms hinges on transforming how learning is assessed..

Keywords: Competence-Based Assessment, STEM Education, Educational Transformation, Formative Assessment, African Framework (CAF-Africa)

1. Introduction

Globally, the United Nations Sustainable Development Goal 4 (SDG 4) calls for inclusive and equitable quality education and the promotion of lifelong learning opportunities for all. Specifically, Target 4.4 emphasizes the need to increase the number of youth and adults with relevant skills for employment, decent jobs, and entrepreneurship. Competence-based assessment is essential to achieving this target, as it ensures that learners are not only knowledgeable but also capable of applying their learning in diverse contexts. Regionally, the African Union's Agenda 2063 and its Continental Education Strategy for Africa (CESA 2016–2025) advocate for transformative education systems that produce African citizens who are innovative, entrepreneurial, and globally competitive. The Science, Technology and Innovation Strategy for Africa (STISA-2024) further emphasize the role of STEM education in driving sustainable development, industrialization, and regional integration. Authentic assessment practices are critical to realizing these ambitions, as they validate learners' ability to solve real-world problems and contribute meaningfully to society.

Nationally, Zambia's 8th National Development Plan (2022–2026) identifies human and social development as a strategic pillar, with education reform positioned as a key enabler of economic transformation. The plan calls for strengthening science, technology, engineering, and mathematics (STEM) education, promoting innovation, and enhancing the quality of teaching and learning. It also emphasizes the need for improved assessment systems that support competence development and lifelong learning. Zambia's 2023 *Education Curriculum Framework* reinforces this shift by explicitly defining education as a tool for human and societal transformation. It emphasizes the development of competences that enable learners to “apply knowledge, skills, attitudes, and values to solve real-life problems” across academic, vocational, and civic domains. The framework prioritizes learner-centered pedagogy, continuous assessment, and the integration of 21st-century skills such as critical thinking, problem solving, collaboration, and innovation. However, despite these progressive policies, assessment systems remain dominated by summative examinations, creating misalignment between classroom practices and policy intentions. Although curriculum reform has gained momentum across the continent, limited empirical research has examined how African educators interpret and enact competence-based assessment in STEM education. This study therefore addresses this gap by analyzing a multi-country discussion among STEM educators to identify how assessment practices can better support competence development across African contexts.

1.1 Background Assessment practices in African education systems have long been shaped by colonial legacies that prioritize summative examinations, often emphasizing factual recall over applied understanding.

These systems were designed to sort learners rather than empower them, with high-stakes exams determining progression, certification, and employment eligibility. As a result, learners were trained to reproduce information rather than demonstrate competence. In recent years, the shift toward Competence-Based Curriculum (CBC) reflects a broader educational reform agenda aimed at aligning learning with 21st-century skills, national development goals, and global competitiveness. CBC emphasizes the integration of knowledge, skills, and values, encouraging learners to apply what they know in real-world contexts. However, while curriculum documents have evolved, assessment systems have remained largely unchanged, creating a disconnect between policy and practice.

This tension is particularly evident in STEM education, where competence involves not only conceptual understanding but also problem-solving, innovation, and collaboration. Without assessment systems that capture these dimensions, CBC risks being reduced to rhetoric. The AfriSTEM WhatsApp discussion provided a rare opportunity to hear directly from educators across ten African countries, revealing both the aspirations and obstacles in transforming assessment from recall to real.

1.2 Problem Statement

Although many African countries have adopted Competence-Based Curricula (CBC), assessment practices remain anchored in summative examinations that emphasize recall over performance. Teachers often lack exposure to authentic assessment design, and systemic accountability structures continue to prioritize grades over competence evidence (UNESCO, 2021). Consequently, CBC implementation risks reproducing outcome-based education (OBC) under a new name unless assessment reform accompanies curricular change.

1.3 Purpose and objectives

- i. Explore how African educators conceptualize competence-based assessment (CBA).
- ii. Identify barriers to CBC assessment fidelity.
- iii. Propose strategies for transforming assessment systems toward authenticity, equity, and empowerment.

1.4 Significance

Transforming assessment determines whether CBC reforms yield practical competence. The study grounds theoretical ideals in real classroom perspectives from African STEM educators.

1.5 Research Questions

- a.RQ1: How do educators define competence-based assessment in African STEM contexts?
- b.RQ2: What challenges impede its implementation in schools?
- c.RQ3: What strategies can ensure alignment between curriculum and assessment?

3 Literature Review 3.1 Competence-Based Education

Competency-Based Education (CBE) focuses on demonstrable integration of knowledge, skills, and attitudes (Pellegrino & Hilton, 2012). It values real-world application over theoretical knowledge. It is an evolving educational paradigm that emphasizes the mastery of specific competencies rather than the mere accumulation of instructional hours or attainment of grades. The roots of CBE can be traced back to the mid-20th century, particularly in response to concerns about the efficacy of education following the launch of Sputnik in 1957, which catalyzed reforms in the U.S. educational system (Hodge, 2007). This model has since gained international recognition, prompting various countries, including Zambia, to adopt it as a means of fostering lifelong learning, critical thinking, and societal engagement (Mulenga & Kabombwe, 2019). In essence, CBE represents a shift from content-based or knowledge-based curricula toward outcome-focused learning, where the "why" of education—competence—is prioritized alongside "what" is taught—content standards (Bramante & Colby, 2012).

Fundamentally, CBE is structured around explicit, measurable, and transferable learning objectives. These objectives are aligned with competencies that students must demonstrate to progress. Unlike traditional education, where time is the variable and learning is assumed to occur over predetermined periods, CBE positions performance as the constant and time as the variable. This paradigm allows learners to progress at individualized paces, advancing only upon actual mastery of competencies, thereby reducing gaps in understanding that can occur in age-based progression models (Sturgis & Casey, 2018; Stafford, 2019). The Zambian education system, for instance, began revising its national curriculum in 2013 to implement a CBE approach, phasing adoption across grades and integrating both academic and vocational pathways to meet the nation's socio-economic needs (Mulenga & Kabombwe, 2019).

CBE employs learner-centered pedagogical strategies that include differentiated instruction, active learning techniques, field-based experiences, and project-based assessments (Aurora Institute, 2019). In doing so, it cultivates higher-order cognitive skills across Bloom's taxonomy—application, analysis, synthesis, and evaluation—thus reinforcing both knowledge acquisition and practical

skill application. Assessment in CBE is formative and ongoing, providing immediate, actionable feedback to enable learners to reflect, iterate, and demonstrate competency effectively. This contrasts with the summative assessment models dominating traditional education systems, wherein success is often approximated through exams rather than the evidence of applied learning (Byrne, Downey, & Souza, 2013).

An essential feature of CBE is the alignment of education with workforce and societal needs. By fostering transferable skills, such as problem-solving, digital literacy, communication, and collaboration, CBE bridges the gap between schooling and real-world applications (American Institute for Research, 2020; Research.com, 2025). In Zambia, this alignment is evident in the vocational pathways, where students obtain trade certificates alongside academic qualifications, integrating certificate programs from TEVETA with the national examinations (MoGE, 2013). Globally, institutions like Western Governors University in the United States and the University of Wisconsin System have demonstrated that CBE can enhance access, retention, and employability by accommodating non-traditional learners, flexible pacing, and evidence-based progression (Aurora Institute, 2019; JETIR, 2024).

Despite these benefits, CBE presents notable implementation challenges. Educators must be trained to design and deliver competency-based instruction effectively; school systems must adapt assessment frameworks to reliably measure mastery, and sufficient resources are critical for sustainable implementation (Mulenga & Kabombwe, 2019; American Institute for Research, 2020). Resistance often arises due to entrenched time-based, content-focused structures in policy and practice. Furthermore, a lack of shared definitions and clear conceptual frameworks for competencies versus learning outcomes can impede clarity in curriculum design and assessment practices (Kelchen, 2016; Evans, Landl, & Thompson, 2021).

Nevertheless, CBE is increasingly recognized as a vehicle for educational equity. By meeting learners where they are and providing individualized support, the model addresses disparities associated with socio-economic status, prior educational experience, or learning differences (Aurora Institute, 2019). It empowers students to take ownership of their learning journey, fostering agency, motivation, and confidence as learners demonstrate mastery of competencies in a transparent, measurable manner.

In conclusion, Competency-Based Education presents a transformative opportunity to modernize education systems to be more learner-centered, equitable, and responsive to societal and workplace demands. While challenges in implementation exist, evidence from both the Zambian context and international case studies suggests that CBE enhances student engagement, skill mastery, and graduate readiness for real-world challenges. Its focus on performance, flexibility, and evidence-based progression highlights the importance of moving beyond traditional content-driven paradigms toward a skills-oriented education that prepares learners not merely to pass examinations, but to demonstrate competence in meaningful, transferable ways (Mulenga & Kabombwe, 2019; Research.com, 2025).

3.2 Assessment for Learning: A Cornerstone of Competence-Based Education

Assessment for Learning (AfL) is a formative approach that positions assessment not as a terminal judgment but as an integral part of the learning process. It is grounded in the belief that assessment should inform instruction, guide learner progress, and foster deeper understanding. Unlike

summative assessment, which evaluates what learners know at the end of a unit or course, AfL emphasizes continuous feedback, reflection, and adjustment—both by the teacher and the learner. Black and Wiliam (1998) were among the first to systematically demonstrate the impact of formative assessment on student achievement. Their research revealed that when learners receive timely, specific, and actionable feedback, they are more likely to engage with learning goals, close performance gaps, and develop metacognitive skills. AfL thus transforms assessment into a learning opportunity, where mistakes are not penalized but used as stepping stones toward mastery. Central to AfL is the use of authentic tasks—learning activities that mirror real-world challenges and require the application of knowledge in context. Wiggins (1998) argued that authentic assessment should demand judgment, innovation, and the ability to transfer learning to new situations. For example, rather than asking learners to recall a physics formula, an authentic task might involve designing a pulley system to lift water in a rural setting. Such tasks not only assess conceptual understanding but also evaluate problem-solving, creativity, and collaboration. Gulikers, Bastiaens, and Kirschner (2004) expanded on this by identifying five dimensions of authenticity in assessment: task realism, physical context, social context, assessment form, and student interpretation. These dimensions are particularly relevant in STEM education, where competence involves not only theoretical knowledge but also practical application. Projects, portfolios, exhibitions, and simulations are common AfL strategies that allow learners to demonstrate integrated competences over time.

However, the implementation of AfL across Africa faces significant challenges. UNESCO (2021) identified uneven CBC implementation across the continent, citing persistent summative orientation, lack of teacher preparation, and resource constraints as major barriers to authentic assessment adoption. Many educators continue to rely on traditional exams due to institutional expectations, limited professional development, and inadequate access to materials and infrastructure needed for performance-based tasks. This disconnect between curriculum intent and classroom practice undermines the transformative potential of CBC.

In the African context, AfL resonates with indigenous pedagogies that value demonstration, participation, and communal learning. It aligns with the Ubuntu philosophy, which emphasizes shared responsibility, reflection, and human development. By embedding AfL into competence-based curricula, educators can create inclusive, culturally responsive learning environments that empower learners to take ownership of their progress. To realize the full potential of AfL, systemic support is essential. Teachers need training in designing authentic tasks, using rubrics, and facilitating peer and self-assessment. Ministries must invest in capacity building, resource provision, and policy alignment. When effectively implemented, AfL not only improves academic outcomes but also nurtures lifelong learners equipped for the complexities of the 21st century. Together, CBE and AfL form the pedagogical and assessment foundation of CBC reforms, yet alignment between the two remains inconsistent in African STEM education. This study is underpinned by constructivist learning theory and assessment for learning principles, which view knowledge as co-constructed through authentic engagement.

4. Methodology

4.1 Research Design This study adopted a qualitative interpretivist design to explore educators' perspectives on competence-based assessment (CBA) within African STEM education. The interpretivist paradigm was appropriate because it focuses on understanding how individuals

construct meaning from their experiences within social and cultural contexts (Creswell & Poth, 2018). The study employed inductive thematic analysis to derive patterns and insights from naturally occurring professional discourse among educators.

4.2 Data Source

Data were obtained from the AfriSTEM multi-country WhatsApp discussion held from 5 to 10 October 2025. The discussion was facilitated by the Directorate of Zambia's National Science Centre and moderated by Professor B. Banda. Participation was voluntary and open to STEM educators across the AfriSTEM network. A 392-entry transcript documenting live exchanges among fifty-two (52) participants representing ten African countries—Zambia, Nigeria, Kenya, Uganda, Ghana, Namibia, Lesotho, Malawi, Mozambique, and Cameroon contributed to the discussion. Participants included classroom teachers, heads of departments, and teacher-trainers engaged in competence-based curriculum implementation. The WhatsApp discussion was used as a virtual focus group because it enabled geographically dispersed educators to exchange ideas asynchronously in a low-cost, interactive environment (Lo Iacono, Symonds, & Brown, 2016). All text messages were exported, anonymized, and converted into a Word document for analysis. Each participant acknowledged that their contributions could be used for academic research under confidentiality conditions.

4.3 Data Analysis

An inductive thematic analysis approach (Braun & Clarke, 2006) was applied to identify recurring ideas and interpret emerging meanings. The data were first read repeatedly to achieve immersion, followed by open coding of phrases and statements related to assessment purposes, task authenticity, teacher capacity, and policy reform. Codes were grouped into broader themes through iterative comparison and refinement. Peer debriefing with two independent reviewers and member checks within the AfriSTEM network enhanced the credibility and trustworthiness of the findings. Reflexive journaling was also used to minimize researcher bias during interpretation. Three overarching themes emerged.

4.4 Ethical Considerations

Ethical approval for the study was obtained from the Zambia National Science Centre Research Ethics Committee. Participation was voluntary, and confidentiality was maintained through the removal of all identifying details from messages. Data were stored securely in password-protected digital folders accessible only to the research team. The study adhered to international guidelines for conducting ethical online research (Markham & Buchanan, 2012).

4.5 Methodological Limitations and Trustworthiness

As with most qualitative inquiries, the findings of this study are context-specific and should be interpreted within the scope of the AfriSTEM network. The use of WhatsApp as a discussion platform limited observation to written expressions, excluding non-verbal cues that could enrich interpretation. Nevertheless, trustworthiness was ensured through several strategies. Credibility was reinforced via peer debriefing, member checks, and triangulation across participants from ten countries. Dependability was achieved through transparent documentation of coding procedures and iterative analysis. Confirmability was strengthened through reflexive journaling to minimize researcher bias, while transferability was supported by providing rich contextual descriptions that allow readers to

judge the applicability of findings to similar educational settings. These measures collectively enhance the rigor and integrity of the study's qualitative design.

5. Discussion of Findings

The analysis of participants' reflections revealed three overarching themes regarding the transition to Competence-Based Education (CBE) assessment practices: (1) assessment purpose should empower learners, (2) authentic contexts make competence visible, and (3) systemic and cultural change is required to sustain reform. These themes highlight the growing awareness among trainees—many serving as Heads of Department (HoDs)—of the transformative intent of CBE assessment and the structural and pedagogical challenges accompanying its implementation.

(verbatim excerpts)

Theme 1: Assessment purpose should empower learners	i. "We need to assess what learners can do with knowledge, not how much they can memorize." — Participant 12 (06/10/2025 04:56 am) ii. "Assessment must develop creativity and innovation, otherwise CBC becomes another name for exams." — Participant 63 (06/10/2025 09:30 am) iii. "Formative assessment turns every learning moment into an assessment opportunity and every mistake into a learning point." — Participant 251 (08/10/2025 08:56 am)
Theme 2: Authentic contexts make competence visible	iv. "Prepare ethanol from leftover nshima... show any other use of the ethanol produced." — Participant 71 (06/10/2025 09:43 am) v. "What would be wrong with pupils developing a mini-industry on school grounds? Assessment becomes realistic." — Participant 74 (06/10/2025 09:49 am) vi. "Competence means demonstrating problem-solving using local materials." — Participant 68 (06/10/2025 09:41 am)

Theme 3: Systemic and cultural change required

- vii. “Many of us insist on summative because it’s what we went through... we fear the unknown and protect tradition.” —
Participant 306 (08/10/2025 07:02 pm)
- viii. “Teachers need continuous CPD for formative assessment; otherwise policy fails at the classroom level.” —
Participant 340 (09/10/2025 06:25 pm)
- ix. “Common Continental Assessment Framework for Africa is key. The African Union needs to champion the move.” —
Participant 277 (08/10/2025 06:32 pm)

Theme 1: Assessment Purpose Should Empower Learners

Participants emphasized that the purpose of assessment in a CBE framework should move beyond measuring recall toward empowering learners to apply knowledge meaningfully. As Participant 12 stated, “*We need to assess what learners can do with knowledge, not how much they can memorize.*” This aligns with the CBE philosophy, which values demonstrable competence rather than rote learning. Participant 63 added that “*Assessment must develop creativity and innovation, otherwise CBC becomes another name for exams,*” reinforcing that assessment should nurture higher-order skills such as creativity, innovation, and critical thinking.

The notion of formative assessment as a continuous learning process was also stressed. Participant 251 explained that “*Formative assessment turns every learning moment into an assessment opportunity and every mistake into a learning point.*” This insight echoes Black and Wiliam’s (2009) argument that formative assessment serves as a feedback mechanism for both learners and teachers, supporting growth rather than judgment. Collectively, these reflections demonstrate a shift among trainees toward recognizing assessment as a developmental tool that empowers learners to demonstrate mastery progressively.

Theme 2: Authentic Contexts Make Competence Visible

The second theme underscores the importance of situating assessment within real-life, problem-solving contexts. As Participant 71 illustrated, “*Prepare ethanol from leftover nshima... show any other use of the ethanol produced.*” Such an example captures the spirit of contextualized learning, where learners use familiar materials to demonstrate scientific competence. Similarly, Participant 74 proposed, “*What would be wrong with pupils developing a mini-industry on school grounds? Assessment becomes realistic.*” These views align with the African Union’s (2019) vision for education systems that produce learners capable of innovating within local economies.

Participant 68’s statement, “*Competence means demonstrating problem-solving using local materials,*” reinforces the idea that authentic, culturally grounded tasks make competence observable and relevant. This perspective reflects constructivist learning theories, which advocate for learning experiences that connect classroom knowledge to real-world application. The trainees’ insights therefore confirm that competence assessment should be contextually grounded and performance-based to accurately capture learners’ capabilities.

Theme 3: Systemic and Cultural Change Required

The final theme highlights the systemic and cultural barriers to CBE adoption. Participant 306 noted, *“Many of us insist on summative because it’s what we went through... we fear the unknown and protect tradition.”* This resistance reflects deep-rooted educational cultures that privilege examinations over performance. The sentiment supports Fullan’s (2007) assertion that meaningful reform requires a shift in mindset and organizational culture, not merely new policy directives.

Participants also acknowledged the need for sustained professional development. As Participant 340 stated, *“Teachers need continuous CPD for formative assessment; otherwise policy fails at the classroom level.”* This underscores the importance of building teacher capacity to interpret and implement assessment reforms effectively. Furthermore, Participant 277 broadened the discussion to a continental scale, asserting that *“Common Continental Assessment Framework for Africa is key. The African Union needs to champion the move.”* This reflects a call for policy harmonization and shared standards to strengthen CBE practices across African education systems.

The findings from the AfriSTEM discussion reinforce the theoretical foundations of competence-based assessment while revealing the practical challenges of implementation. Educators consistently emphasized the need to shift assessment from sorting to empowering—echoing Black and Wiliam’s (1998) call for formative feedback and Wiggins’ (1998) advocacy for authentic tasks. The use of local materials and community-based projects, such as producing ethanol from leftover nshima or developing school-based mini-industries, reflects Gulikers et al.’s (2004) dimensions of authenticity. These examples demonstrate that competence is best assessed through tasks that are meaningful, contextual, and socially relevant.

However, systemic barriers persist. Many educators admitted to defaulting to summative practices due to familiarity, institutional pressure, and concerns about reliability. This highlights the need for cultural change within education systems—moving from compliance to trust, from standardization to contextualization. The proposal for a Common Continental Assessment Framework for Africa (CAF-Africa) is particularly significant. Such a framework could provide shared standards for competence-based assessment while allowing for local adaptation. Regional moderation hubs, professional development networks, and digital platforms could support implementation, ensuring that formative evidence is valued and trusted.

Moreover, integrating indigenous knowledge into STEM assessment not only enhances relevance but also affirms learners’ identities. As Dei (2012) argues, education must empower learners to see themselves as knowledge producers, not just consumers. By aligning assessment with African epistemologies, educators can foster deeper engagement, equity, and innovation.

In summary, the discussion of findings reveals that trainees increasingly understand assessment as a tool for learner empowerment, value authentic and contextualized assessment practices, and recognize the need for systemic cultural transformation. The participants’ reflections affirm that for CBE to be effectively institutionalized, assessment reforms must be accompanied by mindset change, continuous professional development, and regional collaboration to sustain quality and relevance in African education systems. Together, these findings suggest that while there is conceptual alignment with CBE ideals, successful implementation depends on addressing both technical capacity and entrenched cultural practices within schools.

6. Recommendations and Policy Implications

6.1 Policy Recommendations

i. Rebalancing Assessment Weighting Toward Formative Evidence

It is recommended that national education authorities adopt a restructured assessment model that allocates at least 70 percent of learner evaluation to formative assessment evidence, and no more than 30 percent to summative verification. This adjustment aligns with the core philosophy of Competence-Based Education (CBE), which emphasizes learners' ability to apply knowledge, skills, and values in authentic contexts. International research demonstrates that formative assessment enhances learner engagement, supports mastery, and promotes higher-order thinking (Black & Wiliam, 2009). A re-weighted assessment framework would promote continuous learning and reflection, nurturing creativity, innovation, and problem-solving rather than over reliance on recall-driven examinations.

ii. Development of National Guidelines on Authentic Assessment

The Ministry of Education, through the Curriculum Development Centre and the Examinations Council of Zambia, should develop comprehensive national guidelines that mandate the integration of authentic assessment tasks and establish clear moderation protocols. These guidelines should ensure that assessment tools capture performance-based evidence, reflect contextual realities, and maintain reliability and fairness across schools. Institutionalizing such standards would strengthen quality assurance mechanisms and ensure consistency in the evaluation of competencies nationwide.

iii. Continental Collaboration through a common Framework

At the regional level, it is recommended that the African Union (AU) coordinate the creation of a Continental Assessment Framework (CAF–Africa) to harmonize assessment standards and promote shared benchmarks for competence development. This initiative would enhance policy coherence, mutual recognition of qualifications, and inter-country learning mobility. CAF–Africa could further serve as a platform for exchanging best practices, advancing teacher capacity building, and fostering research collaboration among African education systems.

6.2 Implications for Practice

The findings of this study have important implications for educators, school leaders, and training institutions such as the National Science Centre (NSC).

- i. *For Educators:* Teachers need to reorient their instructional approaches to align with formative and performance-based assessment. Continuous professional development (CPD) programs should prioritize practical strategies for designing, implementing, and interpreting authentic tasks that assess learners' competencies holistically.
- ii. *For Heads of Department (HoDs):* HoDs play a pivotal role in cascading CBE principles within their departments. The training strengthened their capacity to lead change, mentor colleagues, and model reflective practice. Sustained leadership support and peer collaboration are essential for embedding a culture of formative assessment within schools.
- iii. *For Training Institutions:* The NSC and similar institutions should allocate more training days for CBE capacity-building programs to allow for deeper engagement with assessment frameworks, digital tools, and reflective practice. Extending the training duration would facilitate mastery, peer exchange, and the development of competence-oriented learning materials tailored to local contexts.

- iv. For Policy Implementers: Successful implementation of these recommendations requires an integrated approach linking policy, practice, and research. Collaboration between ministries, teacher education institutions, and regional bodies will be vital in sustaining momentum toward a truly competence-driven education system in Zambia and beyond.

7. Conclusion

This study highlights the urgent need to transform assessment practices across African education systems—from emphasizing recall of content to demonstrating real competence in authentic contexts. Evidence from the AfriSTEM discussion and the training of Heads of Department revealed that educators increasingly recognize the limitations of summative assessment and the transformative potential of formative, performance-based evaluation to cultivate creativity, innovation, and problem-solving skills.

The ongoing shift from *recall to real* in African STEM education calls for a complete reimagining of assessment practices. Competence-Based Learning must be complemented by Competence-Based Assessment—anchored in authenticity, equity, and learner empowerment. The insights shared by African educators in this study provide a roadmap for this transformation, emphasizing the need for contextually grounded, practical, and inclusive assessment approaches that reflect what learners can *do*, not merely what they *know*.

Moreover, the establishment of a Continental Assessment Framework for Africa (CAF–Africa), led by the African Union, offers a strategic avenue for harmonizing standards, promoting mutual recognition of competencies, and advancing shared educational goals across the continent. Realizing this vision, however, demands systemic and cultural change, sustained professional development, and coherent policy alignment at both national and regional levels.

Ultimately, the future of STEM education in Africa depends on how effectively education systems can bridge the gap between curriculum intent and classroom practice—ensuring that assessment becomes a tool for empowerment, innovation, and lifelong learning rather than mere certification.

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ARTICLE 6

Concept-Driven Geometry Education: Enhancing STEM Learning through Constructivist Approaches

Caroline Taliba

carot819@gmail.com

National Trainer-Mathematics, Ministry of Education and Sports - Secondary Science and Mathematics Teachers' (SESEMAT) Programme, Uganda

ABSTRACT

: In 2023, the Knowledge Co-Creation Programme (KCCP) course "Enhancing Teacher Professional Growth in STEM Education: Towards Effective STEM Learning Outcomes" revolutionized geometry education through a constructivist approach grounded in the Lesson Study model. The course developed a curriculum item and concept map for shapes, integrating two-dimensional (2D) and three-dimensional (3D) shapes from Early Childhood Education (ECE) to societal contexts. Emphasizing 2D shapes as gateways to understanding complex 3D structures is crucial for STEM learning. This paper aims to profile gaps and challenges in current mathematics curricula across African nations, including Uganda, and advocate for concept-driven approaches in mathematics education through insights gained from KCCP participants.

The existing syllabi in Uganda and other African nations like Botswana, Ghana, Malawi, Nigeria, Namibia, and Zambia focus on discrete topics rather than overarching concepts, leading to redundancy and missed opportunities for comprehensive understanding. These curricula emphasize conventional shapes while overlooking irregular objects prevalent in society, aiming to impart knowledge without encouraging the design and construction of products based on theoretical concepts.

Recent studies support concept-based curricula for improving educational outcomes. Hiebert and Grouws (2007) highlight that such approaches facilitate deeper understanding and long-term retention by contextualizing topics in real-world applications. Clements and Sarama (2011) argue for coherent, connected curricula to boost mathematical reasoning and problem-solving skills, consistent with findings from the KCCP course. Analysis of daily reflections gathered over the training period from 11 participants—including teacher trainers, classroom teachers, in-service teacher trainers, and a mathematics curriculum designer—reveals significant repetition and surface learning, prompting recommendations for African curricula to adopt concept-driven approaches.

Keywords: *Concept Mapping, Geometry Education, Lesson Study Model, Curriculum Reform, Real-World Applications*

1.0 Introduction

In the ever-evolving landscape of STEM education, the quest for effective teaching methodologies that cultivate profound conceptual understanding and practical relevance has never been more critical. In 2023, the Knowledge Co-Creation Programme (KCCP) in Zambia embarked on a transformative journey in geometry education, pioneering a constructivist approach rooted in the Lesson Study model. This groundbreaking initiative not only encourages active collaboration among educators but also integrates a robust curriculum item and concept map designed to span from Early Childhood Education (ECE) to real-world societal applications. At its core lies the recognition of two-

dimensional (2D) shapes as foundational elements essential for comprehending intricate three-dimensional (3D) structures—fundamental for advancing STEM disciplines.

Despite these advancements, many African nations, including Uganda, continue to adhere to mathematics curricula that prioritize discrete topics over comprehensive conceptual frameworks. This narrow focus often leads to repetitive content and missed opportunities to foster a holistic understanding of shapes within broader societal contexts. This educational gap persists even as modern paradigms advocate for concept-driven approaches capable of bridging theoretical knowledge with practical applications.

Educational scholars like Boaler (2016) advocate for strategies that promote mathematical thinking through problem-solving and interdisciplinary connections, echoing the objectives of the KCCP initiative. Furthermore, research by Nasir and Hand (2008) underscores the significance of culturally responsive teaching practices in enhancing student engagement and achievement in mathematics. These scholarly insights underscore the urgent need for coherent, connected curricula that deepen student understanding and prepare them for the multifaceted challenges of contemporary STEM landscapes.

By analyzing reflections from a diverse cohort of international and national participants, it becomes evident that African educational systems must urgently embrace concept-driven approaches in mathematics education. Such initiatives promise to enhance learning outcomes, empower educators, and equip students with essential skills for navigating interdisciplinary challenges in the future.

2.0 Objectives

The objectives of this paper are: 1.To share the existing gaps and challenges in current mathematics curricula across African nations, including Uganda, regarding the teaching and learning of geometric shapes.

2.To advocate for the adoption of concept-driven approaches in mathematics education through insights gained from international and national participants, emphasizing deeper learning and real-world application.

3.0 Problem statement

The current mathematics curricula in African nations, including Uganda, often prioritize discrete topics over comprehensive conceptual frameworks. This results in repetitive content and missed opportunities to cultivate a profound understanding of geometric shapes in diverse societal contexts. Despite global advancements in educational theory advocating for concept-driven approaches, these systems struggle to effectively bridge theoretical knowledge with practical applications, limiting students' ability to tackle real-world STEM challenges with confidence. This paper aims to highlight these persistent gaps and challenges within African mathematics education and proposes the adoption of concept-driven methodologies. By emphasizing integrated learning experiences, contextualized applications, and the development of critical thinking and problem-solving skills, this approach aligns with global educational trends that advocate for holistic, real-world learning in mathematics (Boaler, 2016; Nasir & Hand, 2008). The goal is to enhance student learning outcomes, foster interdisciplinary connections, and prepare students to navigate the complexities of modern STEM disciplines effectively.

4.0 Literature Review

In the dynamic landscape of mathematics education, particularly in African nations like Uganda, the prevailing emphasis on discrete topics within curricula often undermines the development of comprehensive conceptual frameworks (Boaler, 2016). This traditional approach tends to foster surface-level learning and rote memorization, which hampers students' ability to engage deeply with real-world challenges, especially in STEM fields where interdisciplinary knowledge and problem-solving skills are essential (Nasir & Hand, 2008).

Global educational trends advocate for concept-driven approaches as a remedy for these shortcomings. Such methodologies integrate mathematical concepts across diverse domains and embed them within real-world contexts, thereby enhancing student engagement and facilitating long-term retention of knowledge (Hiebert & Grouws, 2007; Van de Walle et al., 2019). These approaches are recognized for promoting critical thinking, problem-solving skills, and interdisciplinary connections crucial for success in modern STEM disciplines (Clements & Sarama, 2011).

For example, Hiebert and Grouws (2007) underscore the effectiveness of contextualizing mathematics through real-world applications to deepen understanding and relevance, while Clements and Sarama (2011) advocate for coherent, connected curricula that foster mathematical reasoning across interdisciplinary learning experiences.

Recent studies further highlight the efficacy of concept-based curricula in improving educational outcomes and preparing students for the complexities of contemporary society (Boaler, 2016; Nasir & Hand, 2008). Through an analysis of reflections from participants of the Knowledge Co-Creation Programme (KCCP) in 2023, including teacher trainers and curriculum designers, this study highlights significant gaps in current curricula across African nations and advocates for reforms that prioritize integrated, contextualized learning experiences.

The Lesson Study model emerges as a potent framework within this context, facilitating collaborative inquiry among educators to investigate and refine teaching practices collectively (Stigler & Hiebert, 1999). Anchored in the Lesson Study model, the KCCP's initiative in 2023 transformed geometry education in Zambia by adopting a constructivist approach, exemplifying how Lesson Study can drive teacher professional growth and enhance instructional quality (Lewis & Hurd, 2011; Fernandez & Yoshida, 2004). This integration not only deepens educators' pedagogical content knowledge but also fosters a culture of continuous improvement and knowledge sharing among teachers (Lewis, Perry, & Murata, 2006).

By synthesizing insights from KCCP participants, this research identifies pathways for African mathematics education to embrace concept-driven approaches that bridge theoretical knowledge with practical application, aiming to enhance educational quality, empower educators, and prepare students effectively for the challenges of contemporary STEM disciplines and beyond.

5.0 Methodology

This study adopted a qualitative descriptive research design integrating document analysis, daily reflections, and collaborative inquiry grounded in Lesson Study and concept mapping. This aligns with recommendations by Sandelowski (2000) on the use of qualitative description for capturing natural educational contexts and by Bowen (2009) who supports document analysis as a rigorous method for evaluating curriculum structures. A total of 11 participants—including teacher trainers, curriculum specialists, and classroom teachers—were selected through purposive sampling based on their involvement in curriculum development and instructional practice across different educational levels in Africa.

5.1 Data Collection Methods

Three complementary methods were used:

- i) Document Analysis of mathematics curricula from: Uganda, Botswana, Ghana, Malawi, Nigeria, Namibia, and Zambia. This enabled examination of topic repetitions, fragmentation, and absence of conceptual progression in teaching geometric shapes.
- ii) Daily Reflection Surveys where participants recorded their evolving understanding of:
 - o Concept vs content
 - o Scope and sequencing
 - o Geometry relevance to real-life
 - o 2D–3D conceptual progression
- iii) Collaborative Discussions using Lesson Study cycles and concept mapping to construct a coherent curriculum model from Early Childhood Education (ECE) to societal application.

5.2 Methodological Contribution

By triangulating document analysis, reflection data, and collaborative curriculum design, this study generated practical evidence for transitioning from content-based instruction to concept-driven geometry education, aligned with real-world STEM competencies.

6.0 Results and Data Analysis

6.1 Data Analysis

Data from daily reflections and curriculum documents were analysed using qualitative thematic analysis, following systematic coding procedures that aligned with the problem statement and research objectives. Five key themes emerged:

Table 1: Findings from thematic analysis

Theme	Key Findings / Interpretation
1. Fragmentation and Repetition in Geometry Teaching	Geometry topics such as area, volume, and shapes appeared repeatedly across grade levels without conceptual linkage. Content was recycled instead of developed progressively, leading to surface learning and confusion. As one participant noted, <i>“I realised we teach the same topic every year but never connect it.” (Participant 3)</i>

Theme	Key Findings / Interpretation
2. Concept vs Content Misunderstanding	Educators initially treated content as syllabus coverage. Through reflection, they came to understand that concepts provide the structure of learning, while content should serve the concept — not replace it. As expressed in a reflection, <i>“I focused on finishing topics, not building ideas. Now I understand concepts first.”</i> (Participant 6)
3. Scope and Sequence as a Curriculum Reform Tool	The collaboratively designed scope and sequence (ECE to society) helped participants visualise how geometry could be structured progressively rather than repeated. This was seen as transformative: <i>“For the first time I saw geometry as one complete journey.”</i> (Teacher Trainer 5)
4. Role of Concept Mapping in Conceptual Change	Concept mapping helped teachers visualise relationships between shapes and move away from topic lists, allowing curriculum planning based on learner growth. <i>“The map made me connect ideas instead of just listing them.”</i> (Teacher 3)
5. Shift from Procedural Learning to Deep Conceptual Understanding	Participants shifted from viewing geometry as formula-based to recognising it as a tool for design, innovation, and real-world STEM problem-solving. As one teacher remarked, <i>“Geometry is something we can design with — not just calculate.”</i> (Teacher 4)

These themes demonstrate that combining document analysis, concept mapping, and Lesson Study produces practical evidence for geometry curriculum reform. The study shows that concept-driven learning is not only feasible but necessary for transforming STEM education across African contexts.

7.0 Discussion

7.1 The Concept map on Shapes

The concept map (Figure 2) illustrates how geometric understanding can be structured progressively — beginning with 2D shapes and extending logically into 3D concepts. This visual representation challenges the dominant practice in many African curricula, where geometry is taught as isolated, repetitive topics rather than as a connected pathway of ideas. Topics such as perimeter, area, surface area, and volume are often presented across several grade levels without conceptual linkage, resulting in surface learning and limited transfer of knowledge.

Reflection data validated this issue, with one participant noting, *“We teach perimeter and volume in different years but never show learners how one leads to the other.”* (Participant 6). The concept map provides a corrective approach by positioning 2D shapes as foundational knowledge, which must precede and support understanding of 3D shapes. This aligns with constructivist theory, which maintains that new understanding must grow from prior conceptual structures rather than from memorised facts.

When participants engaged with the concept map during the study, they began to view geometry as an interconnected system of ideas, rather than discrete content to be covered. As one teacher explained, *“The map helped me see geometry as a journey, not just topics.”* (Participant 7). This shift

indicates a move from procedural teaching toward concept-driven curriculum design, where learning is structured around cognitive progression rather than syllabus completion.

Document analysis further revealed that while curricula in several African nations (Uganda, Botswana, Ghana, Malawi, Nigeria, Namibia, Zambia) contain similar topics, they lack conceptual coherence, leading to overlap and shallow instruction. The concept map therefore presents a model for curriculum reform, offering a structured visual framework that supports:

- conceptual progression (2D → 3D), •curriculum coherence across grade levels, •stronger foundations for STEM application, •reduction of topic redundancy.

Thus, the concept map becomes more than a visual tool — it acts as evidence for curriculum restructuring, advocating a shift from content-based repetition to concept-based progression that supports higher-order thinking and real-world STEM problem solving.

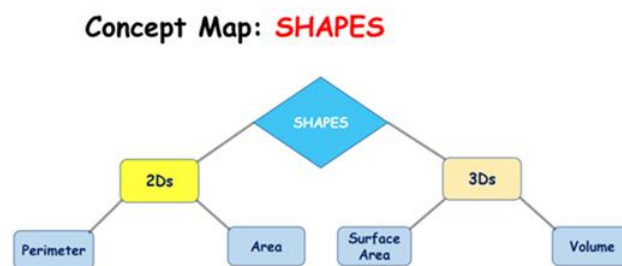


Figure 2: Concept Map Showing Conceptual Progression from 2D to 3D Shapes

These outcomes align with Hiebert & Grouws (2007) and Clements & Sarama (2011), who emphasize that conceptual coherence enhances retention and real-world application. The integration of constructivist approaches and Lesson Study enabled teachers to collaboratively refine teaching materials and reflect on practice. This strengthened pedagogical content knowledge and provided a model for future educational reform.

7.2 Scope and Sequence: Early Childhood Education to Society

A Conceptual Progression of Shapes

To respond to the curriculum gaps identified in the problem statement and supported by findings, a concept-driven scope and sequence for shapes was collaboratively developed during the study. This model demonstrates how geometric understanding can progress logically and developmentally from Early Childhood Education to societal application. Unlike existing curricula—which frequently repeat topics without conceptual linkage—this structure shows how learning can build from 2D foundations toward 3D thinking, spatial reasoning, and real-world STEM innovation.

This scope and sequence provide concrete evidence of how geometry can be planned as a conceptual journey rather than a list of isolated syllabus topics. It directly complements the concept map discussed earlier and serves as a prototype for curriculum reform grounded in constructivist principles and competence-based education.

Table 2: Concept-Driven Progression of Shapes from Early Childhood to Societal Application

Level	2D Conceptual Focus	Transition to 3D Concepts	Emergent Competencies
Early Childhood / Nursery	Naming and recognizing flat shapes	Informal play with boxes, balls & toys (real 3D exposure)	Identify shapes in surroundings
Lower Primary	Draw 2D shapes; understand basic properties	Observe real objects:	Sort objects as 2D vs 3D
Level	2D Conceptual Focus	Transition to 3D Concepts	Emergent Competencies
Upper Primary	Regular vs irregular shapes	Sketch simple 3D forms: cube, prism, pyramid	Begin representing real forms
Lower Secondary	Area & perimeter of irregular shapes	Nets, symmetry, prisms, pyramids	Construct 3D models from 2D nets
Upper Secondary	Formal geometry & transformation	Tetrahedrons, locus, skew lines, projections, angles between lines and planes, volumes, surface area	Use geometry in engineering contexts
Tertiary	Technical drawing & conceptual design	Calculus, differentiation, optimization based on shape behaviour	Product design,
Society Level	Shapes in logos, signage, packaging & art	Architecture, construction, manufacturing, sustainability	Analyse & create design solutions

Although early education formally introduces 2D shapes first, children naturally interact with 3D objects much earlier through everyday play — using boxes, bottles, toys, balls, and logos. However, these experiences are rarely recognised as mathematical learning opportunities. The curriculum analysis confirmed that most syllabi predominantly focus on regular, perfect shapes, while irregular, natural, and artistic forms found in real environments are largely ignored. This creates a disconnection between lived experience and classroom learning, which hampers conceptual development. As one participant noted, “*Children draw 2D shapes at school but play with 3D ones at home. Our curriculum separates them.*” (Participant 4). Another educator reinforced this by saying, “*We teach perfect shapes, but life is full of beautiful irregular ones.*” (Participant 9). These reflections highlight a key curriculum gap — geometry is taught procedurally rather than conceptually, limiting learners’ ability to connect mathematics with reality.

8.0 Recommendations

The findings of this study have implications that go beyond geometry teaching and learning. They speak to the broader aspirations of SDG 4 (Quality Education), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities) and the African Union’s Agenda 2063 – “The Africa We Want”, which calls for a prosperous, innovative, people-centred Africa driven by its youth and by science, technology and innovation. Based on the outcomes of the study, the following recommendations are proposed:

8.1 For Curriculum Designers

- Redesign mathematics curricula so that geometry is concept-driven rather than topic-driven, following a clear progression from 2D to 3D to calculus and modelling, as shown in the concept map and scope–sequence framework.
- Avoid repetition of the same topics in different class levels without conceptual linkages.

Instead, define developmental conceptual milestones across Early Childhood, Primary, Secondary, Tertiary and Society.

- Integrate irregular, natural and artistic shapes (e.g., local crafts, logos, building forms, landscapes) alongside regular shapes to reflect real African environments and culture, contributing to Agenda 2063’s call for culturally grounded development.
- Embed concept maps and scope–sequence charts in official curriculum documents as tools for planning, showing explicitly how geometry concepts grow across levels.
- Make clear links between geometry and STEM pathways (engineering, architecture, design, manufacturing), supporting SDG 9 and Agenda 2063’s focus on industrialisation and innovation.

8.2 For Policy Makers and Education Planners

- Recognise geometry as a strategic subject for STEM and innovation, not just as a set of exam topics. Position geometry as a gateway to engineering, architecture, design and digital industries in policy documents.
- Align curriculum reforms with SDG 4 and Agenda 2063 by emphasising conceptual understanding, creativity and problem-solving rather than syllabus coverage.
- Invest in national and regional professional development programmes that use Lesson Study, concept mapping and curriculum analysis to help teachers implement concept-driven geometry.
- Encourage collaboration between Ministries, Curriculum centres, Universities, Teacher Training Colleges, In-Service Education providers (SESEMAT/SMASE) and Industry to ensure geometry education responds to labour market and community needs.
- Support the development of African-made teaching resources and contextual examples (local housing, markets, transport systems, informal settlements, environmental challenges) that bring “The Africa We Want” into classroom practice.

8.3 For Assessment Bodies and Examination Boards

- Shift from predominantly procedural, recall-based geometry items to tasks that require reasoning, modelling, design and decision-making in real-world contexts.
- Develop assessment frameworks and exemplar banks that include:
 - Interpretation of concept maps and diagrams
 - Design problems (e.g., roofing, packaging, water tanks, community structures)
 - Use of irregular shapes and realistic data
- Align school-based assessment and national examinations with CBC/CBE principles, ensuring that learners demonstrate competence, creativity and critical thinking in geometry.

- Include assessment tasks that reflect SDG 11 (e.g., planning safe, sustainable structures, use of space, urban planning mini-projects).

8.4 For Teacher Education and Continuous Professional Development (CPD)

- Integrate concept mapping, Lesson Study and curriculum document analysis into pre-service teacher education so that new teachers enter schools with conceptual tools, not just content notes.
- Train teachers to
 - Analyse curricula vertically (ECE → Society) to identify gaps and repetition
 - Use real objects and community contexts to teach geometry (local houses, kiosks, boda stages, bridges, markets)
 - Plan lessons around conceptual journeys (e.g., 2D → nets → 3D → calculus/modelling)
- Make reflective Lesson Study cycles a core element of CPD, where teachers jointly plan, teach, observe and refine concept-driven geometry lessons.
- Encourage teacher educators and CPD providers to explicitly link their work to SDG 4 and Agenda 2063, so geometry reform is not seen as an isolated classroom issue but as part of Africa's transformation agenda.

8.5 For Classroom Teachers

- Treat geometry as a story of ideas, not a list of formulas. Start lessons from learners' real experiences with 3D objects (boxes, bottles, houses, art, logos) and connect them back to 2D representations and calculations.
- Use concept maps in lesson planning to show how perimeter, area, surface area and volume are connected, rather than teaching them as separate topics.
- Incorporate irregular and non-standard shapes from the environment to encourage creativity and critical thinking:
 - Roof designs
 - Local craftwork
 - Traditional architecture
 - Market arrangements, gardens, road networks
- Design small project tasks where learners must design or improve something in their community (e.g., a shade, simple shelter, noticeboard, water tank stand) using geometry—thereby linking your teaching to SDG 9 and SDG 11.
- Promote collaborative reflection by discussing which concepts learners struggled to connect and adjusting lesson plans based on that feedback.

8.6 For Communities, Industry and Wider Society

- Schools and communities should partner to show learners how geometry is already being used in:
 - Local housing and construction
 - Tailoring and fashion design

- Furniture making
- Packaging, branding and signage
- Transport design and route planning
- Industry players (construction companies, engineering firms, tech hubs, design studios) can mentor learners and teachers through talks, visits and joint projects, demonstrating the link between classroom geometry and real jobs, in line with Agenda 2063’s vision of a skilled, innovative youth population.
- Encourage community projects where learners use geometry to solve practical problems (simple drainage, shade structures, low-cost teaching aids, recycling-based artefacts), reinforcing the idea that mathematics contributes directly to “The Africa We Want”.

8.7 For Future Research and Regional Collaboration

- Investigate how concept-based geometry teaching influences:
 - Learners’ spatial reasoning and problem-solving
 - Interest in STEM careers
 - Performance in calculus and advanced mathematics
- Conduct cross-country comparative studies within Africa to examine how concept-driven models, such as the one developed in this study, can be adapted and scaled across different contexts.
- Build regional research networks and hubs around concept-driven STEM education, aligned to Agenda 2063 and the Continental Education Strategy for Africa (CESA), so that geometry education reforms feed into broader continental goals.

8.0 Conclusions

This study revealed that geometry in many African curricula is taught as a series of fragmented topics rather than as a conceptual progression. Document analysis and participant reflections confirmed frequent repetition of 2D and 3D topics across levels, with limited linkage to real-world contexts. The concept map and scope–sequence model developed in this study demonstrated how geometry can evolve logically—from early childhood experiences with shapes to advanced reasoning, modelling, and STEM applications.

The findings highlight the need to shift from content-driven teaching to concept-driven geometry education, where 2D shapes serve as the foundation for understanding 3D forms, spatial reasoning, and eventually calculus and design. Such an approach aligns with CBC, CBE, SDG 4 (Quality Education), and Agenda 2063’s vision of a skilled, innovative Africa.

Adopting concept-based approaches can enhance learner understanding, reduce curriculum repetition, and open pathways to STEM careers. Further research is recommended to explore how conceptual learning in geometry influences performance, innovation, and learners’ problem-solving capacity in real-world contexts.

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ARTICLE 7

Unpacking Validity in Competence-Based Assessments through the 3H Model

Peter Mulenga

p.mulenga20@gmail.com

President – Computer Science Teacher’s Association of Zambia (COSTAZ)

Computer Science Teacher – Mungwi Boys Provincial STEM Secondary, Northern, Zambia

ABSTRACT

Africa’s shift toward Competency-Based Curricula (CBC) reflects a continental commitment to education that fosters innovation, practical skills, values, and sustainable development in line with Agenda 2063. However, assessment systems across many African countries remain anchored in colonial, recall-based traditions that weaken assessment validity. This paper examines the validity of Competency-Based Assessment (CBA) practices in Zambia, Uganda, Kenya, and Tanzania using teacher interviews, policy analysis, and document review. Guided by the 3H Model—Head (Cognitive), Hands (Psychomotor), and Heart (Affective)—the study reveals that current assessments overemphasize knowledge recall while neglecting practical performance and values-based competencies. The integrated findings highlight systemic gaps, including insufficient teacher capacity, limited application of indigenous knowledge, and weak alignment with holistic CBC goals. The study proposes an African-centered validity framework based on the 3H Model to strengthen CBA practices across the continent.

1. Description of Terms and Abbreviations

CBC – Competence-Based Curriculum: An educational framework emphasizing mastery of competencies — integrating knowledge, skills, and attitudes to prepare learners for real-world problem solving.

CBA – Competency-Based Assessment: An assessment approach that measures learners’ performance against clearly defined competencies rather than comparing them with others. It focuses on validity, reliability, authenticity, and fairness (BCSEA, 2022).

CBE – Competence-Based Education: An instructional system in which learning outcomes are defined as measurable competencies that learners must demonstrate to progress.

3H Model – Head, Hands, and Heart: An integrated model of learning and assessment developed by Mulenga (2024) that captures cognitive (Head), psychomotor (Hands), and affective (Heart) competencies.

Validity:

The degree to which an assessment accurately measures the intended learning outcomes or competencies.

Reliability:

The consistency of assessment results when repeated under similar conditions.

Authentic

Assessment tasks that mirror real-life contexts, requiring learners to apply their knowledge and skills meaningfully.

Assessment:**Formative**

Assessment for learning, used continuously to provide feedback and guide instruction.

Assessment:**Summative**

Assessment of learning, conducted at the end of a learning period to evaluate overall achievement.

Assessment:**Rubric:**

A scoring guide outlining criteria for evaluating the quality of a learner's performance in line with CBA standards

2. Introduction

The African nations are redefining their education systems through Competency-Based Curricula (CBC), aiming to develop learners who can apply knowledge, demonstrate practical skills, and embody values such as responsibility and ethical citizenship. Despite this progress, assessment practices continue to rely heavily on colonial-style examinations, resulting in a validity gap between curriculum intent and actual evaluation. The 3H Model—Head, Hands, and Heart—provides a culturally resonant framework that aligns with African philosophies such as Ubuntu/Umunthu. It enables holistic evaluation by addressing cognitive, practical, and affective competencies essential for sustainable development under Agenda 2063.

3. Literature Review

Competence-Based Education (CBE) emphasizes mastery learning—where learners demonstrate competencies through applied knowledge and performance (UNESCO IBE, 2016; BCSEA, 2022). The paradigm shifts from traditional to competency-based assessment reorients education from knowledge accumulation to holistic capability development. BCSEA (2022) underscores that Competence Based Assessment (CBA) must integrate three learning domains: the cognitive (knowledge), psychomotor (skills), and affective (values). This aligns directly with Mulenga's (2024) 3H Model, which localizes these domains as Head, Hands, and Heart. Similar approaches have been adopted in Kenya, Rwanda, and Singapore, where assessments integrate project-based tasks, simulations, and reflective exercises (KNEC, 2020; Tan & Lee, 2020). The CBA framework's principles—validity, reliability, authenticity, and fairness—offer critical benchmarks for Zambia's CBC transformation.

4. Problem Statement

Despite Zambia's 2023 implementation of the Competence-Based Curriculum (CBC), assessment practices largely remain traditional, emphasizing factual recall rather than practical and attitudinal competencies. Teachers report limited guidance on developing valid CBA tools and face difficulties integrating psychomotor and affective domains, challenges intensified by the absence of standardized rubrics and authentic, context-based tasks.

As highlighted by BCSEA (2022), assessment validity depends on alignment with real-world competencies, reliability, and fairness **criteria** that current practices do not consistently meet.

This challenge reflects a broader continental trend: although CBC reforms across Africa advocate for holistic learning encompassing knowledge, skills, and values, assessment systems remain dominated by cognitive recall inherited from colonial examination models.

Consequently, learners are insufficiently prepared to address African challenges such as climate resilience, digital inequity, food security, and indigenous innovation.

These gaps underscore the urgent need for a culturally grounded assessment framework that captures holistic learner development and aligns with Africa’s transformative educational goals

5. Research Objectives

1. Examine the validity of CBA frameworks in African countries.
2. Identify gaps between current assessment and holistic competency development.
3. Demonstrate how the 3H Model enhances assessment validity.
4. Promote integration of African knowledge systems and sustainability in assessments.

6. Research Questions

1. Do you use Competence Based Assessment Framework (CBAF) from MoE to help you create valid CBAs?
2. What do you usually incorporate in your Assessments?
3. How effective are your methods of measuring learners’ real competencies?

7. Research Methodology

The study employed a qualitative descriptive design targeting 20 secondary school teachers from Northern, Copper belt, Lusaka, and Eastern provinces. Data collection involved interviews, focus groups, and document analysis. Secondary data included policy documents and guides such as the BCSEA (2022) Test Item Development Guide and the Zambia CBC Framework (CDC, 2023). The-matic analysis was used to identify recurring issues related to validity, teacher capacity, and integration of the 3H Model.

8 Sampling

A total of 215 teachers, purposively selected from Zambia, Tanzania, Kenya, and Uganda, participated in the study. These teachers were drawn from diverse school settings—urban, peri-urban, and rural—to ensure a broad representation of experiences and practices across the region. Purposive sampling was used to target teachers who had direct experience with implementing competence based curricula, conducting assessments, or supervising learner projects, as their expertise was essential for providing rich and credible data. The inclusion of participants from four countries allowed for meaningful cross-country comparisons and offered insights into both shared challenges and unique national contexts within East and Southern Africa's evolving competency-based education landscape. 215 purposively selected teachers from Zambia (185), Tanzania (22), Kenya (5), and Uganda (3) participated

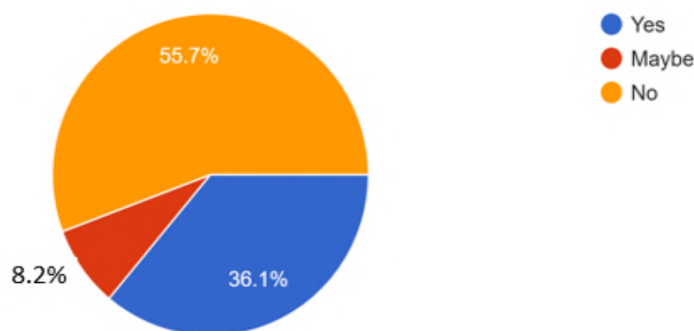
9. Data Collection

Data for the study were gathered using multiple complementary sources to ensure depth and validity. Semi-structured interviews were conducted with key stakeholders, including teachers to capture their experiences, perceptions, and insights on existing assessment practices. In addition, national assessment policy documents were analyzed to understand the official frameworks, expectations, and guidelines shaping assessment within the education system. Examination papers and learner projects were reviewed to examine the types of tasks, competencies assessed, and the extent to which they reflect practical, inquiry-based, and context-responsive learning. Finally, school-level rubrics and assessment tools were collected to explore how individual schools interpret and implement competency-based assessment in practice. Together, these data sources provided a comprehensive picture of assessment policies, practices, and gaps across different levels of the education system.

10. Findings and Discussion

Do you use Competence Based Assessment Framework (CBAF) from MoE to help you create valid CBAs

215 responses



The figure above showed that 55.7% did not use any framework for assessment, 8.2% were not sure and 36.1% were sure of using the framework.

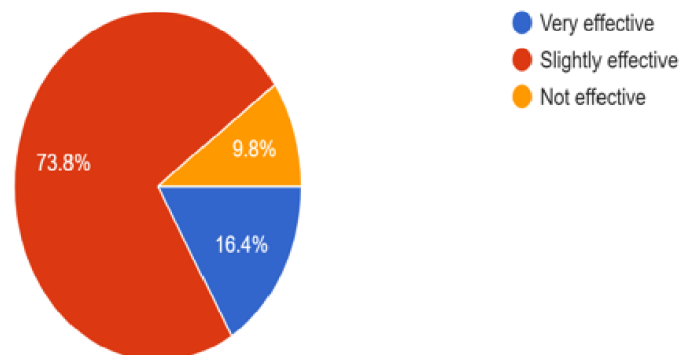
Select what you incorporated in your Assessments?



The figure above revealed the assessment domain coverage **blue bar** represents **HEAD** (cognitive), red bar **HEART** (Values attitudes, empathy), and yellow bar **HANDS** (practical skills).

In your opinion, how effective are your methods of measuring learners' real competencies

215 responses



The figure above showed that 73.8% said their assessment were slightly effective, 9.8% said were not effective and only 16.4% said their current methods were very effective.

Findings reveal persistent gaps in teacher competence, limited resources, and lack of standardization. Approximately 75% of teachers expressed difficulty designing assessments that capture practical and affective learning competencies. BCSEA (2022) emphasizes that valid assessments should test learners' ability to transfer knowledge and values to new situations, ensuring the assessment measures both process and product. In Zambia, overreliance on written tests contradicts these principles. Implementing the 3H Model within CBA ensures holistic validity Head addresses cognitive mastery, Hands measures applied competence, and Heart evaluates attitudes and ethical reasoning. The guide's call for authenticity, fairness, and flexibility strengthens this alignment.

11. Proposed Structure of a Valid CBA using 3H Model

The 3H Model is a holistic assessment approach that evaluates learners in three domains **Head**, **Hands and Heart**, ensuring competence in knowledge, skills, and values.

Based on BCSEA (2022) and Mulenga (2024), a valid CBC assessment should balance formative and summative modes and encompass four integrated sections:

1. Knowledge and Recall (Head)
2. Understanding and Application (Head → Hands)
3. Practical Performance Tasks (Hands)
4. Values and Attitudes Demonstration (Heart)

The 3H Mulenga's Assessment Model

A balanced approach to comprehensive learning assessment



CBA Components

Integrating the 3H model

3H Domain	How to Incorporate in Assessment	Examples of Assessment Tools
Head (Cognitive)	Assess learners' understanding, reasoning, and application of knowledge.	Written tests, quizzes, oral questions, problem-solving tasks.
Hands (Psychomotor/Skills)	Evaluate learners' ability to perform tasks, demonstrate skills, and apply knowledge in practical situations.	Practical exams, projects, simulations, lab work, demonstrations.
Heart (Affective/Values)	Assess attitudes, values, teamwork, responsibility, and ethical behavior.	Peer assessment, self-assessment, observation checklists, reflective journals.

Each section must employ authentic, context-based tasks that demonstrate the learner's ability to integrate knowledge, perform skills, and exhibit values. The assessment design must adhere to principles of validity, reliability, authenticity, fairness, and cognitive complexity as outlined by BCSEA (2022).

12. Conclusion

Current Outcome-Based / Competency-Based Assessments focus mainly on **knowledge (Head)**. **Skills (Hands)** and **values/character (Heart)** are often overlooked. That creates a **validity gap**, as assessments do not fully reflect the holistic goals of the Competency-Based Curriculum (CBC).

Africa cannot realize true educational transformation without decolonizing its assessment systems. The 3H Model bridges global standards and African values, promoting holistic, authentic, and sustainable learning.

Learners who think critically (Head), act creatively (Hands), and live ethically (Heart) will drive Africa's transformation.

13. Recommendations

- Develop a Pan-African CBA framework grounded in the 3H Model and African indigenous philosophies.
- Create CBC assessment rubrics that clearly define competencies for Head (knowledge), Hands (skills), and Heart (values).
- Integrate indigenous innovation, local materials, and sustainability practices into all assessments.
- Strengthen teacher capacity through continuous CPD on competency mapping, holistic item writing, and contextual task design.
- Replace recall-based testing with real-world, problem-based assessments rooted in African contexts.

-
- Promote regional benchmarking and collaboration across African countries to share best practices.
 - Establish 3H Innovation Awards to recognize learners who demonstrate balanced competencies and indigenous creativity

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ARTICLE 8

Modernizing Mathematics and Science Education in Rwandan Secondary Schools Through Project-Based Learning

Jeannette Muterampundu¹, Ezechiel Nsabayezi¹, Aloys Iyamuremye¹, Venuste Nsengimana², Pheneas Nkundabakura³, Theophile Nsengimana³, Eugenie Uwamariya⁴

muterampunduj@yahoo.fr

¹African Centre of Excellence for Innovative Teaching and Learning Mathematics and Science (ACEITLMS), University of Rwanda-College of Education (UR-CE), Kayonza, Rwanda

²University of Rwanda-College of Science and Technology (UR-CST), The Centre of Excellence in Biodiversity and Natural Resource Management, Kigali, Rwanda

³University of Rwanda-College of Education (UR-CE), Kayonza, Rwanda

⁴Rwanda Basic Education Board, Kigali, Rwanda

ABSTRACT

Improving mathematics and science education is pivotal to Rwanda's reform, emphasizing Project-Based Learning (PBL). Yet, PBL implementation remains teacher-centered, constraining collaboration, critical thinking, and problem-solving, despite policy advocating learner-centered approaches. A mixed research approach was used to collect and analyze data. In this regard, data were collected from 120 secondary school teachers using structured questionnaires and semi-structured interviews, and from 320 students using a 21st century skills questionnaire. Quantitative data were analyzed using descriptive and inferential statistics, while qualitative data were analyzed thematically. Findings revealed that teachers perceive PBL as highly effective in enhancing engagement (mean = 4.62, SD = 0.48) and conceptual understanding (mean = 4.54, SD = 0.51). Significant differences emerged by teaching experience ($F(2,117) = 4.21, p < 0.05$) in favor of experienced teacher but no significant effect with regard to gender and educational level ($p < 0.05$). Thematic analysis further identified three dominant themes: (1) promotion of learner-centered practices, (2) the need for ongoing professional support, and (3) challenges related to limited teaching resources and time constraints. The study concludes that PBL has transformative potential to modernize science and mathematics instruction and equip learners with critical 21st century skills. Based on these findings, teachers are recommended to embrace project-based learning in the teaching of science and ma. The policymakers should prioritize systematic teacher training and provide adequate resources required to implement PBL. Future research also should explore the longitudinal impact of PBL on lifelong learning and entrepreneurial skills.

Keywords

: Project-Based Learning, Mathematics and Science Education, 21st-Century Skills, Rwanda, and Teacher Professional Development.

1.Introduction

In the 21st century, education systems worldwide are experiencing a paradigm shift from traditional teacher-centered approaches to learner-centered pedagogies that emphasize critical thinking, creativity, collaboration, and problem-solving (Herlinawati et al., 2024). This shift is largely influenced by the growing recognition that today's learners require more than rote memorization to thrive in dynamic, technology-driven societies. Mathematics and science education, as the backbone of

Science, Technology, Engineering, and Mathematics (STEM) fields, play a central role in preparing students to navigate complex global challenges such as climate change, technological innovation, and sustainable development (Maspul, 2024). To achieve this goal, project-based learning (PBL) has emerged as one of the most effective pedagogical strategies for modernizing teaching and learning in STEM disciplines.

Project-based learning is an instructional method that engages students in investigating authentic, real-world problems over extended periods, integrating knowledge from multiple disciplines to create meaningful outcomes (Zhang, 2022). Unlike conventional lecture-based methods, PBL fosters deeper conceptual understanding, promotes learner autonomy, and bridges the gap between classroom theory and practical application. Through projects, learners are encouraged to apply mathematical and scientific concepts in contexts relevant to their lives and communities, thus enhancing motivation and long-term retention (Chang et al., 2022). Globally, the implementation of PBL in STEM education has been associated with improved academic performance, higher-order thinking, and the development of 21st-century competencies (Al-Thani & Ahmad, 2025; Aran, 2024).

Across developed and developing nations, there has been a renewed effort to reform mathematics and science curricula to reflect 21st-century learning goals. Countries such as Finland, Singapore, and South Korea have embraced inquiry-based and project-oriented pedagogies that promote collaboration, innovation, and contextualized learning (Lee & Lee, 2025). In African contexts, educational modernization has been driven by the African Union's Agenda 2063 and the Sustainable Development Goal 4 (SDG 4), which emphasize quality and equitable education for all (UNESCO, 2022). These frameworks advocate for competency-based education that empowers learners to solve real-world problems and contribute to national development. Consequently, project-based approaches are being increasingly recognized as tools for bridging the gap between knowledge acquisition and application (Diana et al., 2021). However, the effective adoption of such approaches in sub-Saharan Africa remains constrained by resource limitations, large class sizes, limited teacher preparation, and traditional assessment systems that prioritize memorization over inquiry and problem-solving (Age, 2025; Chistyakov et al., 2023).

Rwanda's education system has undergone significant transformation over the past two decades, guided by the country's Vision 2050 and the Ministry of Education's commitment to building a knowledge-based economy. The introduction of the Competence-Based Curriculum (CBC) in 2015 marked a pivotal step toward modernizing education, emphasizing learner-centered pedagogies, digital literacy, innovation, and entrepreneurship (REB, 2016). Mathematics and science subjects are central to this reform because they underpin technological advancement and national development priorities.

Despite these reforms, several studies have identified persistent challenges in achieving effective learning outcomes in Rwandan secondary schools. Research indicates that while teachers are aware of the CBC principles, many still rely heavily on traditional didactic methods due to limited pedagogical skills, insufficient instructional materials, and large student-to-teacher ratios (Gasana et al., 2024). Consequently, students often perceive mathematics and science as abstract, difficult, and disconnected from real-life applications (Nsengimana et al., 2024). This disconnect undermines learners' motivation and limits the development of critical and creative thinking skills that the CBC seeks to nurture.

Project-based learning provides a promising pathway to actualize the goals of Rwanda's CBC by linking theory to practice. It enables students to explore authentic problems, collaborate in groups, and present findings that demonstrate both knowledge and application (Ndahimana & Nkundabakura, 2023). PBL aligns well with Rwanda's policy emphasis on active learning, innovation, and problem-solving (Ukobizaba et al., 2025). Moreover, integrating PBL in mathematics and science classrooms could foster scientific inquiry, mathematical reasoning, and the development of transferable skills such as teamwork, communication, and entrepreneurship.

However, empirical studies examining the implementation and outcomes of PBL in Rwandan secondary schools are still limited. While the CBC encourages learner-centered approaches, the extent to which project-based learning has been adopted and its impact on students' academic and non-academic competencies remains unclear. Teachers often express uncertainty about how to design, facilitate, and assess projects that align with curriculum standards while meeting examination requirements (Ndayisenga, 2025). Thus, there is a need for systematic inquiry into how PBL can effectively modernize mathematics and science education within the unique contextual realities of Rwandan schools.

The theoretical foundation of project-based learning is grounded in constructivist learning theory, particularly the works of Piaget (1973) and Vygotsky (1978). Constructivism posits that learners actively construct knowledge through experiences, reflection, and social interaction (Al Abri et al., 2024). Within a PBL environment, learners engage in inquiry processes that require them to integrate prior knowledge with new information to solve complex problems. Vygotsky's social constructivism further highlights the importance of collaboration and scaffolding, which are central features of PBL. Students learn from peers and teachers through guided interaction, gradually achieving higher cognitive competence. Additionally, experiential learning theory (Kolb, 1984) supports PBL by emphasizing the cyclical process of doing, reflecting, conceptualizing, and applying a sequence inherent in project-based tasks.

In this context, the modernization of mathematics and science education in Rwanda requires innovative pedagogical practices that cultivate both academic excellence and transferable skills. While the CBC offers a strong policy foundation, its success largely depends on how teachers translate learner-centered principles into classroom practice. PBL, as an active learning strategy, offers the potential to transform traditional classrooms into dynamic learning spaces that promote exploration, collaboration, and innovation. Yet, despite its potential, there is limited empirical evidence on the extent of PBL adoption in Rwandan secondary schools, teachers' readiness to implement it, and its impact on students' engagement and achievement. Therefore, understanding how PBL contributes to modernizing mathematics and science education is critical for policymakers, curriculum developers, and educators seeking to achieve the national goals of quality and relevant education. This study thus seeks to fill this research gap by examining the application of project-based learning in Rwandan secondary schools, its benefits, challenges, and implications for educational modernization.

2. Research Objectives

The main aim of this study is to explore how Project-Based Learning (PBL) can modernize mathematics and science education in Rwandan secondary schools. Specifically, the study seeks to:

- a) Examine the current practices and extent of integration of project-based learning in teaching mathematics and science in Rwandan secondary schools.
- b) Analyze the effects of project-based learning on students' motivation and engagement, and in mathematics and science subjects.
- c) Identify the challenges and opportunities associated with implementing project-based learning in the Rwandan secondary school context.

3. Research Questions

To achieve these objectives, the study is guided by the following research questions:

- a) To what extent is project-based learning currently integrated into the teaching and learning of mathematics and science in Rwandan secondary schools?
- b) How does project-based learning influence students' motivation, engagement, and achievement in mathematics and science education?
- c) What are the key challenges and enabling factors that affect the implementation of project-based learning in Rwandan secondary schools?

4. Research methodology

4.1. Research approach and design

The research design adopted was a convergent parallel design, which allowed the researcher to collect both quantitative and qualitative data concurrently, analyze them separately, and integrate the results during interpretation. This design was particularly suitable because it facilitated comparison and corroboration of the numerical trends with the rich of narrative perspectives of teachers and students (Greer & Abel, 2022). The use of a mixed approach aligns with contemporary education research standards that emphasize methodological pluralism to address complex educational reforms such as the adoption of project-based learning. This study employed a mixed-methods research approach, integrating both quantitative and qualitative paradigms to obtain comprehensive insights into how Project-Based Learning (PBL) contributes to the modernization of mathematics and science education in Rwandan secondary schools. The rationale for adopting this approach lies in its ability to triangulate findings from multiple data sources, thereby enhancing the validity and depth of the study (Creswell, 1999). In this sense, the quantitative component provided measurable evidence on teachers' and students' perceptions, practices, and attitudes toward PBL, while the qualitative component offered contextualized explanations of how and why these patterns emerged.

4.2. Sample and Sampling technique

The target population comprised lower secondary school mathematics and science teachers and students enrolled in general secondary schools in Rwanda. These schools were purposefully due to the fact that their teachers were attended training on Project, Based Learning. In this context, teachers were chosen as key informants because they are directly responsible for implementing the Competence-Based Curriculum (CBC) and PBL strategies in classrooms, while students were included to provide firsthand insights into learning experiences and engagement in project-based activities. In the light of the above, a sample of 120 teachers and 320 students was selected using a combination of stratified random sampling and purposive sampling techniques. Stratified sampling was employed

to ensure proportional representation of both mathematics and science (Chemistry, Biology, and Physics) teachers from each school. Within each stratum, random selection ensured fairness and minimized sampling bias. Students were selected purposively from classes where project-based activities were being conducted under teacher guidance. This ensured that participants had relevant exposure to PBL practices. The Table 1 shows the demographic information of participants.

Table 1. Demographic information of participants

Category Variables Frequency (n)

Teachers (n = 120)

Gender	Male	68
	Female	52
Subject specialization	Mathematics	33
	Science (Physics, Chemistry, Biology)	87
Teaching experience	1–3 years	32
	4–5 years	48
	Above 5 years	40
Educational qualification	Bachelor's degree (Ao)	74
	Diploma (A1)	46
School type	Public	71
	Government-aided	49

Students (n = 320)

Gender	Male	166
	Female	154
Grade level	Senior one	112
	Senior two	96
	Senior three	112

4.3. Method of data collection

Multiple data collection instruments were used to collect both quantitative and qualitative data in alignment with the mixed-methods approach. A structured questionnaire was developed for teachers to capture their perceptions, experiences, and practices concerning project-based learning. This questionnaire comprised five sections: demographic information, knowledge of PBL principles, implementation practices, perceived impact on students' learning, and challenges faced in implementation. All items were measured on a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5). The questionnaire was subjected to expert review and pilot testing to ensure clarity and content validity before the main data collection. In addition, a 21st-century skills questionnaire was administered to students to assess their competencies in collaboration, communication, creativity, and critical thinking as influenced by PBL experiences. The instrument was adapted from the (Sahin et al., 2019) The items were organized into four categories: learning and innovation skills, information and media literacy, life and career skills, and participation in project-based learning tasks. Responses were recorded on a five-point Likert scale ranging from “never” to “always.” The use of this instrument provided quantitative data on how project-based learning contributed to students' development of essential 21st-century skills. To enrich the quantitative data, semi-structured interviews were conducted with 10 teachers and 20 students purposively selected from the participating schools. The interviews explored deeper insights into teachers' experiences with project-

based learning, challenges encountered, institutional support mechanisms, and perceived impact on student performance and engagement. Interviews lasted between 30 and 45 minutes, were audio-recorded with permission, and were supported by field notes to capture non-verbal cues and contextual observations.

4.4. Method of data analysis

Quantitative data analysis was carried out using the Statistical Package for Social Sciences (SPSS) version 26. Data cleaning and coding were performed prior to analysis to ensure accuracy and completeness. Descriptive statistics such as means, frequencies, and standard deviations were computed to summarize teachers' and students' responses. To determine whether there were significant differences in teachers' perceptions based on demographic characteristics such as teaching experience, gender, and educational qualification, inferential statistics were applied. Specifically, a one-way Analysis of Variance (ANOVA) was used to test for variations across experience levels and qualifications, while independent-sample t-tests examined gender-based differences. The significance level was set at 0.05. Additionally, correlation analysis was conducted to examine the relationship between the extent of PBL implementation and indicators of student engagement and performance. These analyses helped to identify key predictors and factors influencing successful implementation of project-based learning in mathematics and science classrooms.

The qualitative data were analyzed thematically using Braun and Clarke,(2021)six-phase framework. This involved familiarization with the data through repeated reading of transcripts, generating initial codes, searching for themes, reviewing and defining themes, and producing the report. An inductive coding process was used, allowing themes to emerge naturally from participants' narratives. The analysis revealed three dominant themes: the promotion of learner-centered practices, the need for continuous professional development for teachers, and challenges associated with limited teaching resources and time constraints. The themes provided nuanced understanding of how teachers experienced the transition from traditional teaching to project-based learning approaches. The integration of qualitative and quantitative findings during interpretation enabled a more comprehensive understanding of the effectiveness and challenges of PBL in Rwandan secondary schools.

4.5. Validity and reliability of the research instruments

Validity and reliability were key considerations in this study. Content validity was ensured through expert evaluation by three specialists in science education and curriculum design from the University of Rwanda College of Education (UR-CE). These experts reviewed the instruments to confirm their alignment with research objectives and appropriateness of wording. Construct validity was further enhanced through pilot testing with 20 teachers and 30 students from non-participating schools, which helped refine the instruments by removing ambiguous items. For the student questionnaire, factor analysis was conducted to confirm the dimensional structure corresponding to the 21st-century skill categories. Triangulation of data sources and methods further strengthened the study's validity by confirming the consistency of findings across different participant groups and instruments. Reliability was evaluated through Cronbach's Alpha coefficient, which yielded 0.87 for the teacher questionnaire and 0.84 for the student questionnaire, indicating high internal consistency. In qualitative analysis, reliability was ensured through member checking, whereby participants reviewed their transcribed interviews to confirm accuracy, and through peer debriefing sessions among the research team to minimize subjective bias during coding and interpretation.

5. Result interpretation

This section presents the findings of the study based on the objectives and research questions outlined earlier. Both quantitative and qualitative results are integrated to provide a comprehensive understanding of how Project-Based Learning (PBL) modernizes mathematics and science education in Rwandan secondary schools.

Quantitative results

5.1. Current practices on the Integration of Project-Based Learning in Teaching

Mathematics and Science

Table 2 presents the results on the current practices regarding the extent of integration of PBL in their classrooms. Teachers reported a high degree of integration of Project-Based Learning (PBL) into mathematics and science instruction (overall mean = 4.36, SD = 0.57). The strongest practice was encouraging collaborative work on real-life problems ($M = 4.51$, $SD = 0.49$), followed by designing projects aligned with CBC objectives ($M = 4.42$, $SD = 0.57$). Assessment based on project outcomes ($M = 4.34$, $SD = 0.61$) and ICT integration in project work ($M = 4.18$, $SD = 0.64$) were slightly lower but still indicate substantial adoption. These results suggest widespread teacher endorsement and implementation of PBL, with opportunities to strengthen ICT-supported project activities.

Table 2. Current practices of the integration of PBL in teaching Mathematics and Science

Statements	Mean	SD
I design projects that align with CBC objectives	4.42	0.57
I encourage students to work collaboratively on real-life problems	4.51	0.49
I assess students based on project outcomes and presentations	4.34	0.61
I integrate ICT tools in project work	4.18	0.64
Overall	4.36	0.57

The results of the one-way ANOVA presented in the table 3 showed that only teaching experience had a statistically significant effect on the integration of Project-Based Learning (PBL) in teaching mathematics and science ($F(2,117) = 4.21$, $p = 0.017$). Specifically, teachers with more than five years of experience demonstrated a higher level of PBL implementation ($M = 4.52$, $SD = 0.47$) compared to those with 1–3 years of experience ($M = 4.21$, $SD = 0.63$). This indicates that experienced teachers are more confident and skilled in designing and facilitating project-based activities. In contrast, no significant differences were found based on gender, subject specialization, educational qualification, or school type ($p > 0.05$).

Table 3. Inferential analysis on teacher's current practices with regard to gender, subject, teaching experience, qualification, and school type

Category	Variable	Mean	SD	F	p-value	Significance
Gender 0.397	Male	4.38	0.54	0.72	0.284	Not significant
	Female	4.33	0.60			
Subject specialization	Mathematics	4.29	0.58	1.16	0.284	Not significant

	Science (Phy, Chem, Bio)	4.39	0.55			
Teaching experience	1–3 years	4.61	0.63	4.21	0.017	Significant
	4–5 years	4.36	0.51			
	Above 5 years	4.52	0.47			
Educational qualification	Bachelor's (Ao)	4.38	0.53	0.83	0.364	Not significant
	Diploma (A1)	4.32	0.60			
School type	Public	4.35	0.56	0.27	0.604	Not significant
	Government-aided	4.38	0.57			

5.2. Effectiveness of PBL on students' Motivation and Engagement in mathematics and science

The student questionnaire revealed that PBL significantly enhances motivation and engagement. The results in Figure1 shows that students frequently engage in teaching and learning activities.

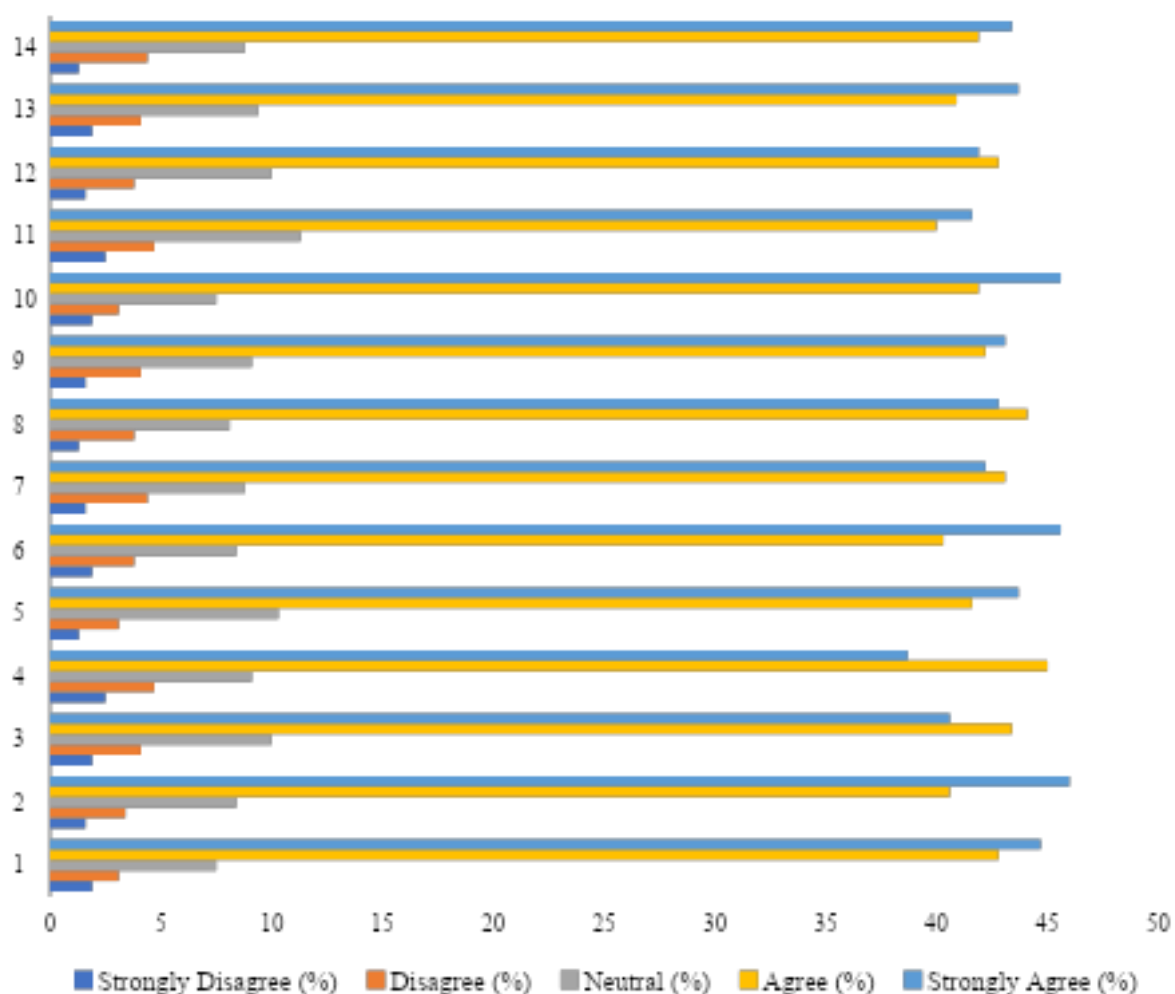


Figure 1. Students' perception on influence of PBL on their motivation and engagement

The results in the Table 4 presents inferential analysis of the influence of PBL with regard to gender. The independent-samples t-test revealed no statistically significant gender differences in students' perceptions of Project-Based Learning (PBL) effectiveness on either motivation ($t(318) = 0.98$, $p = 0.329$) or engagement ($t(318) = 1.12$, $p = 0.263$). Both male and female students reported high levels of motivation and engagement (mean scores above 4.3 on a 5-point scale), indicating that PBL fosters a uniformly positive learning experience across genders. The small effect sizes (Cohen's $d = 0.11$ and 0.13) further confirm that the differences were negligible, suggesting that PBL equally supports both male and female learners in developing interest, participation, and commitment in mathematics and science learning.

Table 4. Inferential analysis on students' perception of PBL with regard to gender

Variable	Gender	Mean	SD	t(df)	p-value	Cohen's d
Motivation	Male	4.43	0.51	0.98 (318)	0.329	0.11
	Female	4.38	0.53			
Engagement	Male	4.41	0.55	1.12 (318)	0.263	0.13
	Female	4.35	0.57			

5.3. Challenges affecting PBL implementation in teaching and learning mathematics and science

Thematic analysis of interviews identified three main challenges affecting effective PBL implementation: limited instructional materials, insufficient time for projects, and inadequate teacher training. Teachers expressed that large class sizes and rigid examination systems constrain their ability to integrate projects fully into the curriculum. Conversely, the study revealed enabling factors such as strong administrative support, collaborative culture among teachers, and student enthusiasm for practical learning experiences.

The figure 3 summarizes the frequency of major themes that emerged from qualitative data analysis.

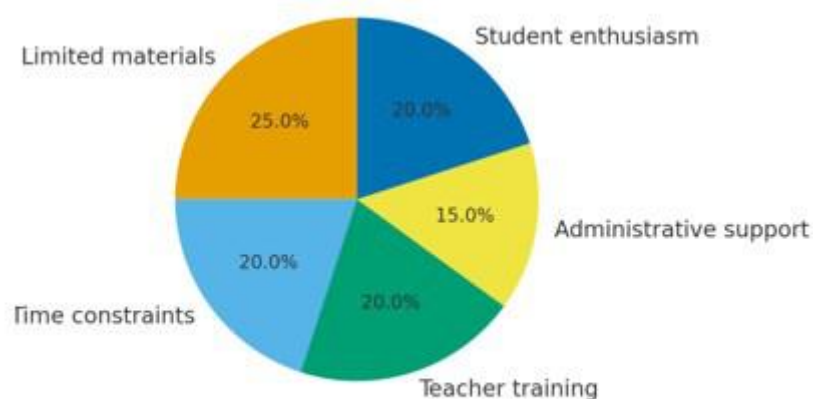


Figure 2. Challenges faced by teachers and students while implementing PBL approach

The qualitative results revealed both challenges and opportunities associated with the implementation of PBL approach in three main themes.

Theme one: Infrastructure and resource limitations A major challenge to the successful implementation of Project-Based Learning (PBL) in Rwandan secondary schools is the lack of infrastructure and resources. Schools, especially in rural areas, often lack the necessary educational tools such as computers, reliable internet access, and lab equipment needed to execute complex, research-oriented projects. This gap in resources directly limits the effectiveness of PBL, which relies heavily on technology and materials for student

collaboration and exploration.

"Without proper resources like computers or the internet, it is hard for students to explore the full potential of project-based learning. We try to make do, but it feels like we're always working with one hand tied behind our backs." Student also added "Sometimes we have to use old textbooks for research, and it's frustrating when we can't find the information we need. If we had better access to technology, we could do so much more in our projects. "While some schools are making efforts to overcome this challenge, the disparity in resource availability across regions highlights a significant barrier to consistent implementation of PBL.

Theme two: Teacher preparedness and pedagogical skills Another challenge that impedes the success of PBL is the lack of teacher preparedness and training. Many teachers in Rwanda are accustomed to traditional, teacher-centered methods of instruction, such as lecturing and rote memorization. The shift to a more student-centered approach, which is core to PBL, requires teachers to not only redesign their lesson plans but also to adopt new pedagogical strategies for guiding and assessing project work. One teacher said, "I am used to lecturing and giving exams. It's hard to let go of the traditional teaching methods and trust students to drive their own learning. I need more training to understand how to facilitate PBL properly." A students also commented that "We are always told what to do in class, but with PBL, I want to learn how to lead my project. I wish our teachers were more involved in guiding us through the process."The lack of professional development opportunities for teachers in PBL strategies limits their ability to facilitate meaningful project-based experiences for students. There is a clear need for targeted training programs to equip teachers with the skills needed to support the transition from traditional to project-based teaching.

Theme three: Time constraints and curriculum pressures The pressure to cover a dense curriculum and prepare students for national exams creates time constraints that hinder the full integration of PBL. Given the traditional focus on exam preparation, teachers often struggle to find sufficient time to plan and execute extended projects, which require a more flexible and long-term approach to learning. Teacher reported "The curriculum is so packed that it's hard to find time for projects. Even when I want to implement PBL, I feel pressured to finish the syllabus before the exams. It's a constant balancing act." The student added "We don't have enough time for everything. It's like we're always rushing through lessons and then suddenly we're expected to do projects. It's hard to manage both." This mismatch between the time required for PBL and the demands of the national curriculum creates a significant tension. Teachers feel the weight of preparing students for exams, which often takes precedence over more dynamic learning experiences like project-based learning.

5.4. Opportunities regarding to the implementation of PBL approach in teaching mathematics and sciences

Theme one: Development of 21st-Century Skills One of the most compelling opportunities offered by PBL is its ability to foster 21st-century skills, including critical thinking, collaboration, creativity,

and problem-solving. These skills are increasingly essential in the modern global economy, and PBL offers a practical, hands-on approach to developing them. Students actively engage in real-world projects that require them to solve problems, work with others, and think critically skills that are crucial for future success. One teacher said "With PBL, I see my students learning how to think critically, solve real-world problems, and collaborate with others. These are the skills they need to succeed in the future, and I am excited to help them develop these skills." The student also complements this statement of teacher by saying that "I love working on projects because they make me think differently. Instead of just memorizing facts, I get to figure out how to solve actual problems, and that feels more useful." The opportunity to learn in an active, hands-on way helps students prepare for the challenges of the 21st century, equipping them with the skills that will be vital for their future careers and personal development.

Theme two: Increased student engagement and ownership

PBL increases student engagement by giving learners more autonomy over their education. Instead of being passive recipients of knowledge, students are encouraged to take ownership of their learning through active participation in projects that interest them. This leads to increased motivation and a deeper understanding of the material. A mathematics teacher noted. "I've noticed that students who struggle in traditional classes thrive in PBL settings. They become more involved and take pride in their work. It's amazing to see how they evolve when given the freedom to explore topics that interest them." Her student said that "When we work on projects, I feel like I have a say in my education. I get to explore my interests, and that makes me care more about what I'm learning." This shift towards active learning helps students develop a sense of responsibility for their education, which not only increases engagement but also fosters a deeper commitment to learning.

Theme three: Collaboration and community involvement

PBL also provides an opportunity to engage with the local community. By collaborating on projects that address real-world issues, students can work with local organizations, businesses, and government bodies. This interaction fosters a sense of social responsibility and allows students to apply their learning in meaningful ways. One teachers said that "One of the most rewarding aspects of PBL is seeing students work with local businesses or community leaders. It's a win-win situation: students gain practical experience, and the community benefits from their ideas." A chemistry student also said that "I really enjoyed working on a project with a local organization. We researched environmental issues in our area, and then we presented solutions to the community. It felt amazing to make a real impact. "Through these collaborations, students gain insights into local issues, develop solutions that directly benefit the community, and build a sense of connectedness to the world beyond the classroom.

6. Discussion

This study provides compelling evidence that Project-Based Learning (PBL) constitutes a powerful strategy for transforming mathematics and science education in Rwandan secondary schools. The findings show that teachers increasingly apply project-based approaches that prioritize collaboration, inquiry, and authentic problem-solving core principles of learner-centered pedagogy. This mirrors international studies in which PBL has improved student engagement, conceptual understanding, and higher-order thinking (Hall & Miro, 2016; Moallem, 2019). Similar to results reported by

Billah et al. (2019), the present study confirms that PBL nurtures student motivation and autonomy by linking abstract theory to real-world contexts.

The study also found that experienced teachers are more adept at implementing PBL effectively, echoing findings from Aidoo (2023) that emphasize the influence of pedagogical experience on inquiry facilitation. This suggests that sustained professional development remains central to successful reform. Rwanda's current Competence-Based Curriculum (CBC) promotes active learning, yet as Markula and Aksela (2022) observed, many teachers still rely on traditional approaches due to limited resources. The present study reinforces this challenge, revealing that inadequate materials, heavy workloads, and exam pressure continue to constrain classroom innovation.

Notably, the study's qualitative data align with Vygotsky's (1978) social constructivist theory, showing that students learn effectively through collaboration and peer interaction. When students design projects to solve community problems, they move from rote learning toward applied understanding a trend also identified in (Chang et al. ,2022). This outcome directly supports the goal of Rwanda's Vision 2050 to produce creative and entrepreneurial citizens capable of applying STEM knowledge to national development. The absence of significant gender disparities in engagement and achievement parallels prior evidence from Wang (2021) who argue that inclusive pedagogies like PBL democratize participation. The finding that both male and female students benefited equally underscores PBL's potential to promote equity in STEM learning an outcome long sought in African education reforms (UNESCO, 2022). Furthermore, the consistency of results with studies from other contexts (Lee & Lee, 2025; Herlinawati et al., 2024) suggests that

PBL's benefits are globally replicable when local contextual factors such as teacher support and curriculum alignment are adequately addressed.

Nevertheless, implementation barriers persist. Teachers cited inadequate training, limited ICT tools, and insufficient time as major obstacles issues that mirror those documented in Age (2025) and Chistyakov et al. (2023). These challenges indicate that PBL adoption requires not only pedagogical reform but also systemic transformation. Continuous professional development programs should emphasize design thinking, assessment literacy, and reflective practice to help teachers manage project complexity effectively. Ultimately, this study reinforces that PBL is more than a pedagogical choice; it is a catalyst for educational modernization. By connecting classroom learning to real-life applications, it embodies Dewey's (1938) vision of experiential education. When scaled and supported through coherent policy and resources, PBL can serve as a cornerstone for Rwanda's transition to a knowledge-based economy and a model for other nations seeking to reform STEM education in resource-limited settings.

7. Implications for policy, practice, and research

The implications of these findings are far-reaching for different educational stakeholders. Firstly, for policymakers, the study highlights the necessity of institutionalizing PBL as a standard pedagogical approach within the CBC framework. This requires adequate resourcing especially provision of laboratory equipment, ICT infrastructure, and project materials. Moreover, assessment systems should be reformed to value inquiry processes and project outcomes alongside traditional examinations. Such alignment between pedagogy and assessment is critical to sustaining innovation in teaching and learning. Secondly, For teacher education institutions, the results advocate embedding PBL

principles within pre-service and in-service training programs. Teacher preparation curricula should emphasize project design, interdisciplinary integration, and authentic assessment practices. Establishing Community of Practices (CoP) or Professional Learning Communities (PLCs) in schools can facilitate peer mentoring, reflective dialogue, and collaborative curriculum planning practices proven to enhance teaching efficacy and reform sustainability. Thirdly, for school leaders, fostering a supportive school culture that encourages experimentation, collaboration, and innovation is crucial. Administrators should provide time and incentives for teachers to engage in joint planning and resource sharing. Partnerships with universities and local industries could further strengthen project relevance and bridge school-community gaps. Lastly, for researchers, this study opens several avenues for future inquiry.

Longitudinal studies are needed to examine the sustained impact of PBL on academic achievement, creativity, and lifelong learning. Further, mixed-methods studies that integrate classroom observations, performance analytics, and student portfolios could offer richer insights into how PBL fosters complex skill development. Comparative studies across regions or subject areas could also illuminate contextual factors influencing success.

8.Limitations and future directions

While this study provides evidence, certain limitations must be acknowledged. The reliance on self-reported data introduces potential social desirability bias, as teachers may overstate their implementation levels. Additionally, the cross-sectional design limits causal inference about long-term impacts of PBL on student outcomes. Future research employing experimental or longitudinal designs could more accurately capture these dynamics.

1.Conclusion and recommendations

This study concludes that Project-Based Learning significantly contributes to modernizing mathematics and science education in Rwanda by fostering learner engagement, collaboration, and real-world application of knowledge. It strengthens the alignment between classroom practice and the Competence-Based Curriculum's emphasis on critical thinking, creativity, and problem-solving. PBL not only enhances students' cognitive understanding but also cultivates transferable 21st-century skills essential for Rwanda's socio-economic transformation. However, the approach's sustainability is hindered by resource limitations, insufficient teacher preparation, and rigid assessment systems. It is therefore recommended that the Ministry of Education and the Rwanda Basic Education Board institutionalize continuous professional development focusing on PBL design, facilitation, and assessment. Schools should establish professional learning communities to promote peer mentoring and reflective practice. Policymakers must invest in ICT tools, laboratory facilities, and flexible curricula that allocate sufficient time for projects. Finally, future research should employ longitudinal and experimental designs to examine PBL's long-term effects on student achievement, creativity, and entrepreneurial skills. With coherent support at all levels, PBL can transform Rwandan classrooms into innovation-driven spaces that prepare learners to meet the challenges of the 21st century.

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Conflict of interest

Authors declare no any potential conflict of interest regarding to the publication of this manuscript.

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ARTICLE 9

Formative First: Rebalancing African Education Assessment Systems Toward Continuous Competence Measurement

Benson Banda, Anecetus Moonga, Eric Bbabbi - Ministry of Education Directorate of National Science Centre – Lusaka, Zambia
and Muhydeen Ahmed - Nigeria

ABSTRACT

African education systems continue to rely heavily on high-stakes summative examinations despite global reforms advocating formative, continuous assessment to enhance competence development. This study explores assessment practices across ten Science Technology Engineering & Mathematics (STEM) secondary schools in Zambia to understand the extent to which formative assessment is implemented and the systemic barriers that hinder its adoption. Using a mixed-methods design, data were collected through surveys, interviews, and classroom observations. Findings reveal a significant imbalance between formative and summative assessment practices, with summative approaches dominating instructional processes. Teachers demonstrate strong familiarity with summative exams but limited capacity to design formative tasks and provide constructive feedback. Classroom observations further show minimal use of continuous assessment strategies, creating a gap between policy aspirations and classroom realities. The discussion argues that this imbalance undermines competence-based curriculum reforms, particularly in STEM learning environments that require iterative feedback. The study concludes that rebalancing assessment systems toward formative approaches is essential for aligning classroom practice with competence-based outcomes. Recommendations include strengthening national formative assessment policies, investing in teacher professional development, and introducing digital tools to support feedback tracking.

Keywords: *formative assessment, summative assessment, competence-based curriculum, continuous assessment, Zambia, STEM education.*

Introduction

Assessment remains one of the most influential elements shaping teaching and learning processes in African education systems. Globally, there has been a growing shift towards formative assessment as a mechanism for improving learning outcomes and ensuring that learners acquire competencies rather than memorised knowledge (UNESCO, 2022). Formative assessment is central to competence-based education reforms embraced by many African countries, including Zambia. Despite this policy direction, education systems across the continent continue to be dominated by high-stakes summative examinations, which determine learner progression, certification, and placement. The heavy emphasis on summative assessment narrows the curriculum and limits opportunities for deep learning and creativity.

Continental initiatives such as the Continental Assessment Framework for Africa (CAF-Africa) aim to harmonise learning measurements and strengthen national assessment systems (African Union, 2024). Regional assessments, including Programme for the Analysis of Education Systems (PASEC) and Southern and Eastern Africa Consortium for Monitoring Educational Quality (SEACMEQ),

similarly provide valuable insights into literacy and numeracy outcomes. However, these largescale assessments remain summative and do not directly influence daily feedback mechanisms that occur in classrooms. This gap highlights the need to rebalance assessment approaches and prioritise continuous formative feedback that supports learning.

Within Zambia, the Ministry of Education (2023) underscores continuous assessment as a core element of the competence-based curriculum. Yet implementation remains weak due to limited teacher capacity, inadequate training, and absence of clear assessment guidelines. Teachers often struggle to design performance-based tasks, apply rubrics, and document learner progress effectively. Consequently, formative assessment practices are inconsistently applied,

overshadowed by the pressures of preparing learners for national examinations.

This study explores current formative and summative assessment practices across STEM secondary schools in Zambia. It identifies challenges teachers encounter in implementing continuous assessment and proposes strategies for strengthening formative assessment within competence-based frameworks. Through a mixed-methods analysis, the study offers evidence-based recommendations for policymakers, teacher training institutions, and school leaders.

Literature Review

Global education literature emphasises the indispensable role of formative assessment in enhancing learner achievement. Black and Wiliam (1998) demonstrated that formative assessment significantly improves learning outcomes when teachers provide timely, meaningful feedback and involve learners in self-evaluation. Their work argues that formative assessment is most effective when integrated consistently into instruction rather than applied occasionally.

In Africa, assessment practices remain predominantly summative despite curriculum reforms. UNESCO (2022) notes that although many African countries have adopted competence-based curricula, classroom assessment practices lag behind due to weak teacher preparation and limited resources. CAF-Africa and CESA 2024 call for balanced assessment approaches that support competency development (African Union, 2024). However, implementation studies reveal persistent gaps between policy and practice. Kanjee and Sayed (2019) observe that teachers often view assessment primarily as grading rather than a process for improving learning.

In Zambia, similar trends emerge. The Ministry of Education (2023) mandates continuous assessment, but research shows inconsistencies in implementation. Studies by Mwanza (2021) and Chishimba (2020) point to inadequate teacher training, unclear guidelines, and limited monitoring mechanisms as major barriers. These challenges hinder the development of practical skills and authentic learning experiences essential for STEM education. The literature therefore indicates that rebalancing assessment systems requires investment in teacher capacity, digital tools, reduced exam pressure, and assessment cultures that value learning rather than certification.

Methodology

This study employed a mixed-methods research design combining quantitative and qualitative approaches to obtain a comprehensive understanding of assessment practices in STEM secondary

schools across Zambia. The mixed-methods design was selected to triangulate findings and strengthen the validity of the results, as recommended by Creswell (2014).

The study sample consisted of ten STEM-focused public secondary schools purposively selected based on their involvement in competence-based curriculum implementation. Quantitative data were collected through structured teacher surveys that examined assessment frequency, types of assessment used, teacher confidence, and training history. A total of 120 teachers participated in the survey.

Qualitative data were gathered through semi-structured interviews with 20 teachers and 10 school administrators to gain deeper insights into their experiences and challenges with formative assessment. Classroom observations were conducted to document actual assessment practices and compare them to self-reported data. Observation checklists captured the presence of peer assessment, self-assessment, feedback practices and use of rubrics.

Data analysis involved descriptive statistics for quantitative responses, while qualitative data were analysed using thematic coding. The triangulation of multiple data sources enhanced the reliability and depth of the findings. Ethical considerations, including informed consent, confidentiality, and voluntary participation, were strictly observed throughout the study.

Major Findings and Discussion

The findings of this study clearly highlight deep structural and pedagogical imbalances between formative and summative assessment practices in the sampled STEM schools. The dominance of summative assessment—accounting for nearly 80% of all classroom evaluation activities—indicates that teaching and learning remain largely exam-driven. Summative instruments such as tests, quizzes, and end-of-term examinations continue to shape instructional priorities, teacher planning, and learner engagement. This pattern is consistent with regional trends in African education systems, where national examinations heavily influence curriculum interpretation and classroom decision-making (UNESCO, 2022). The heavy reliance on summative assessments reinforces a culture of high-stakes testing that often narrows learning to recall-based competencies rather than broader problem-solving abilities.

In contrast, formative assessment practices were used sparingly and constituted approximately 20% of total assessment activities. Moreover, the formative practices observed—mainly oral questioning, informal feedback, and homework checks—fall short of structured formative assessment approaches advocated in competence-based education models. Effective formative assessment involves deliberate processes such as peer assessment, self-assessment, descriptive feedback cycles, learning progressions, and performance-based tasks—all of which were either minimally applied or absent in observed classrooms. The absence of such practices suggests limited teacher capacity to translate formative assessment policy into meaningful pedagogical action. This gap mirrors UNESCO's (2022) assertion that African teachers require strengthened assessment literacy to engage effectively with contemporary approaches that priorities learning rather than the measurement of learning outcomes.

Teacher interviews reinforced this conclusion by revealing significant confidence gaps in designing and implementing formative assessment tasks. Many teachers acknowledged that while they were comfortable constructing tests and quizzes, they had not received adequate training in formative

strategies aligned with competence-based learning. They identified several barriers, including limited professional development opportunities, insufficient time for planning formative activities, and the absence of clear, user-friendly guidelines on implementing continuous assessment. These barriers reflect broader systemic challenges documented in African contexts, where shifts toward competence-based curriculum reforms have not been matched with comprehensive teacher support structures (African Union, 2024). The lack of ongoing professional development undermines teachers' ability to integrate assessment seamlessly into instruction.

Classroom observations further revealed that instructional practices were strongly oriented toward preparing learners for high-stakes examinations. Lessons were predominantly teacher-centred, with limited opportunities for learner autonomy, inquiry, or reflective engagement. Such environments constrain the application of formative assessment strategies that require active learner participation, such as peer evaluation and self-reflection. This contradicts the intentions of Zambia's Competence-Based Curriculum (Ministry of Education, 2023), which emphasises practical application, creativity, collaboration, and continuous monitoring of learner progress. The current assessment imbalance therefore restricts learners' ability to acquire critical 21st-century skills, particularly in STEM subjects that require experimentation, reasoning, and iterative feedback. Another critical finding concerns the substantial gap between policy intentions and classroom reality. Although Zambia's national education policies mandate continuous assessment as part of the teaching and learning process, teachers lacked functional frameworks and digital tools for documenting learner progress. Many schools still rely on manual record-keeping, which teachers described as time-consuming and impractical for large classes. Without technological support—such as digital assessment platforms, automated feedback tools, or electronic learner profiles—teachers are unable to systematically track and respond to individual learning needs. This observation aligns with African Union (2024) reports which argue that policy reforms fail when implementation does not include resourcing, monitoring, and sustained teacher empowerment. The implications of these findings are significant for learner outcomes. When formative assessment is poorly implemented, learners receive limited feedback on their progress, reducing their ability to understand strengths, address learning gaps, and develop metacognitive skills. The imbalance also perpetuates inequities; as summative assessments often disadvantage learners who require additional support during the learning process. In STEM subjects, where conceptual understanding must be built progressively, the absence of continuous formative feedback limits learner progression and contributes to persistent performance challenges. A shift from assessment of learning to assessment for learning is therefore essential to support holistic growth and sustained academic achievement.

Overall, the study underscores the need for systemic interventions that prioritise formative assessment as a central component of teaching and learning. Strengthening formative assessment is not merely a pedagogical adjustment but a structural reform that requires coordinated action across teacher training institutions, ministries of education, and school leadership. Effective implementation must include curriculum-aligned guidelines, ongoing professional development, technological investments, and monitoring frameworks that reinforce continuous assessment. Without these supports, the goals of competence-based education and improved STEM performance will remain unattainable.

Conclusion

The study set out to explore how assessment practices in STEM classrooms align with the aspirations of competence-based education reforms in Zambia and across Africa. The findings demonstrate a clear and persistent imbalance between formative and summative assessment practices, with the latter overwhelmingly dominating classroom evaluation. While summative assessments remain essential for measuring overall achievement, their disproportionate use—constituting approximately 80% of all assessment activities—has created an exam-driven learning culture that restricts opportunities for deeper understanding, creativity, and critical thinking. This misalignment undermines the core objectives of competence-based curricula, which priorities continuous skill development, application of knowledge, and learner autonomy.

The limited use of formative assessment, often implemented in informal and inconsistent ways, highlights significant gaps in teacher assessment literacy, professional support structures, and policy implementation capacity. Teachers' lack of confidence, inadequate training opportunities, and the absence of practical tools for documenting learner progress further weaken efforts to embed continuous assessment into daily classroom practice. As a result, formative assessment—an essential component of effective teaching and learning—remains peripheral rather than integral to instructional processes.

The study concludes that meaningful transformation of assessment systems requires a holistic and systemic approach. Strengthening formative assessment cannot be achieved through policy directives alone; it demands deliberate investments in teacher professional development, provision of user-friendly assessment tools, development of clear guidelines, and supportive leadership at school and national levels. By rebalancing assessment practices towards continuous, learner-centred, and competence-oriented methods, education systems can better support holistic learner growth and improve performance in STEM subjects. Ultimately, transitioning from assessment of learning to assessment for learning is not only desirable but essential for advancing the goals of equitable and high-quality education across Africa.

Recommendations

Based on the findings, the study recommends the following:

1. Strengthen National Policies and Guidelines on Formative Assessment

Clear, practical, and standardised national guidelines are needed to translate competence-based curriculum expectations into everyday classroom practice. These guidelines should include exemplar tasks, assessment rubrics linked to learner competencies, and structured procedures for feedback, documentation, and reporting. Strengthened policy clarity will reduce inconsistencies and help teachers understand how formative assessment should function within STEM learning contexts.

2. Enhance Teacher Professional Development and Assessment Literacy

Given the capacity gaps identified, continuous professional development (CPD) is essential. Training should focus on practical, classroom-embedded formative strategies such as peer assessment, self-assessment, feedback cycles, and performance-based tasks. The Ministry of Education and teacher training institutions should integrate comprehensive assessment literacy within both pre-service and in-service programmes to build sustained competence among teachers.

3. Provide Digital Tools and Resources for Continuous Assessment

The limited capacity to document learner progress highlights the need for accessible digital assessment tools. Introducing simple, user-friendly platforms for recording formative evidence, generating feedback, and tracking competencies will reduce the administrative burden on teachers. Implementation should be accompanied by digital literacy support and infrastructure investment, especially in resource-constrained schools.

4. Promote Classroom-Level Integration of Formative Assessment

Schools should embed formative assessment within daily instructional routines rather than treating it as an add-on. Departmental meetings should be used for collaborative planning of formative tasks, sharing best practices, and aligning assessments with curriculum competencies. Leadership support is crucial in fostering a classroom culture where continuous feedback, learner participation, and reflection are prioritized.

5. Strengthen Supervision, Monitoring, and Support Systems

District and school leaders must adopt supportive monitoring approaches that focus on improving formative assessment quality rather than merely compliance. Classroom observations, mentoring, and feedback from supervisors can guide teachers toward effective integration of formative strategies. Monitoring systems should capture both formative processes and learner progress to ensure alignment with competence-based education objectives

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ARTICLE 10

EMPOWERING WOMEN AND GIRLS' PARTICIPATION IN SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS (STEM) AS LEADERS OF AFRICA'S SUSTAINABLE FUTURE

Nelson K. Koech

koech.nelson9@gmail.com

TSC, Kenya

ABSTRACT

This paper expl

ores strategies for empowering women and girls to participate and lead in STEM fields as a critical component of Africa's sustainable development. The theme is Reimagining STEM for a Pan-African Future: Bridging Education, Innovation, and Sustainable Development Towards Agenda 2063. Despite numerous efforts, gender gaps persist in STEM education and careers. The Sub-theme is Gender Equity in STEM: Empowering Women and Girls as Leaders of Africa's Sustainable Future. The objective is to address systematic barriers to women's participation in STEM by analyzing the effectiveness of policy reforms, mentorship programs, and inclusive pedagogies. The paper reviews gender-responsive policy reforms across Africa, mentorship initiatives such as those led by African Women in Science and Engineering (AWSE), and the integration of inclusive teaching practices championed by institutions like CEMASTEIA. Employing a qualitative comparative research design, data is collected through document analysis, including reports from CEMASTEIA, UNESCO, and various African ministries of education. Analytical techniques are thematic analysis for qualitative data and basic descriptive statistics for quantitative trends. Data from ten African countries, mentorship programs, and inclusive classroom practices are presented through charts and tables to visualize participation trends, implementation outcomes, and access disparities. The findings reveal that while notable strides have been made, challenges in implementation, access, and sustainability remain. The paper concludes with targeted recommendations to strengthen policy enforcement, expand mentorship access, and enhance gender-sensitive pedagogy. Overall, this paper underscores the necessity of systemic transformation to achieve gender equity and empower women as leaders in Africa's STEM future.

CHAPTER 1: INTRODUCTION

1.0 Introduction

Women and girls remain underrepresented in Science, Technology, Engineering, and Mathematics (STEM) in Africa. This disparity hampers the continent's ability to fully benefit from diverse perspectives and innovative capacities. Empowering women in STEM is essential for sustainable development, as outlined in Agenda 2063.

1.1 Research Objective

To address systematic barriers to women's participation in STEM by exploring policy interventions, mentorship programs, and inclusive pedagogical approaches.

1.2 Research Question

How can systematic barriers to women's participation in STEM be addressed to foster gender equity and leadership?

1.3 Operational Definition of Terms

CEMASTE

: Centre for Mathematics, Science and Technology Education in Africa **COMSTEDA**: Conference on Mathematics, Science and Technology Education in Africa **STEM**: Science, Technology, Engineering, and Mathematics

CHAPTER 2: LITERATURE REVIEW

2.0: Introduction

The global landscape reveals significant gender disparities in STEM. According to UNESCO (2019), women account for only 28% of the global STEM workforce. In developed countries, systemic efforts such as scholarships, affirmative policies, and outreach campaigns have led to slow but steady increases in female participation.

In Africa, the disparities are more pronounced due to compounded barriers such as poverty, cultural norms, limited access to quality education, and lack of mentorship.

However, initiatives such as the African Union's CESA 16-25 and Agenda 2063, and national strategies in Kenya, Rwanda, and South Africa have started shifting the landscape.

2.1: Agenda 2063

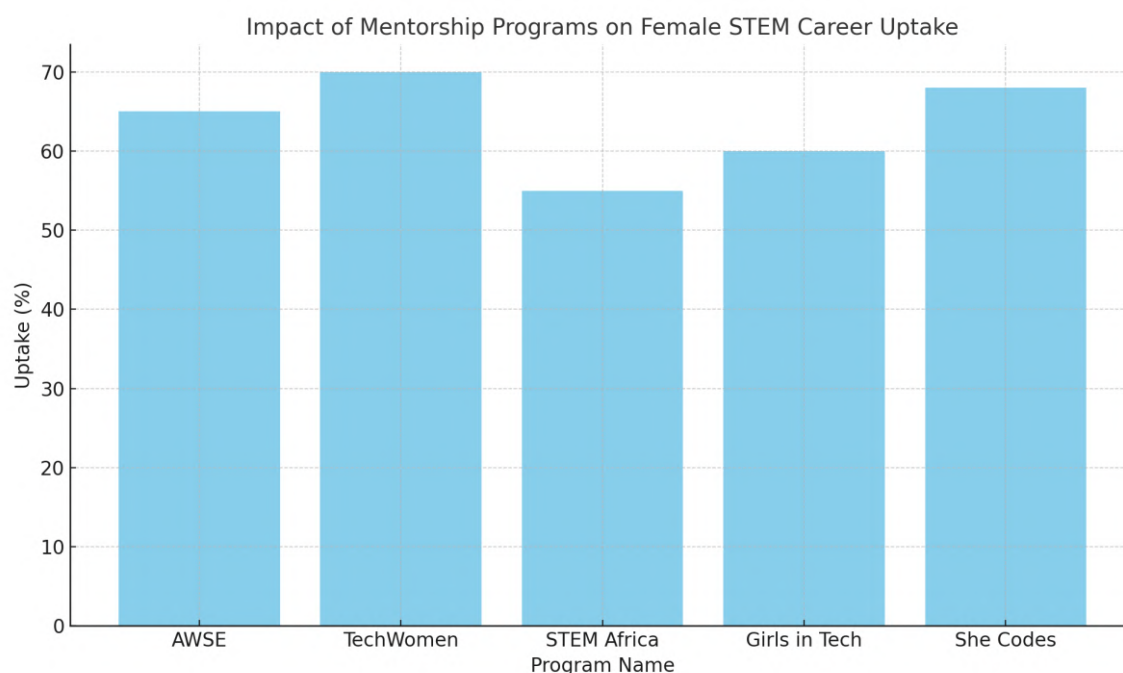
Agenda 2063 is the African Union's blueprint for transforming the continent into a global powerhouse. Aspiration 6 of the agenda emphasizes inclusive growth and development, including gender equality. This vision includes the empowerment of women and girls through access to quality education, particularly in science and technology fields. STEM education is seen as vital for industrialization, innovation, and sustainable development, making women's participation a critical component.

2.2: Policy Reforms

Policy frameworks across Africa are evolving to include gender equality clauses in STEM education. Nations like Kenya and Rwanda have implemented gender-responsive education policies. The African Union's Continental Education Strategy for Africa (CESA 16-25) supports this shift (AU, 2020).

2.3: Mentorship Programs

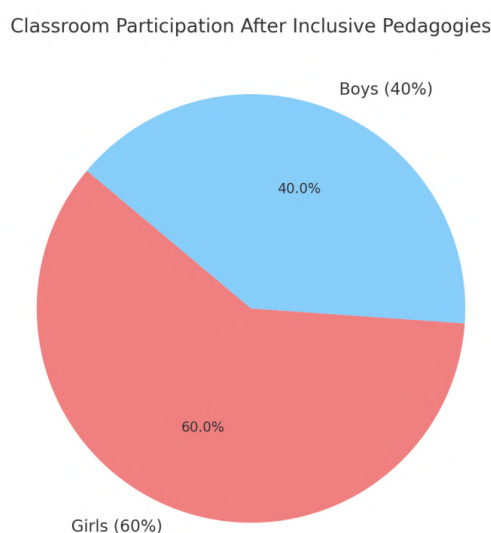
Mentorship has proven to be a key driver for women's success in STEM. Organizations like African Women in Science and Engineering (AWSE) provide role models and support networks. Such programs enhance retention and build confidence (Mbote, 2021).

Figure 1: Impact of Mentorship Programs on Female STEM Career Uptake

Source: Author's data presentation (2025)

2.4: Inclusive Pedagogies to Achieve Agenda 2063's Equity Aspirations

Inclusive pedagogical strategies, such as gender-sensitive teaching, participatory learning, and the use of ICT, can foster supportive environments for girls in STEM. Teachers trained through CEMASTEIA demonstrate improved delivery and gender inclusiveness (Njoroge, 2022).

Figure 2: Classroom Participation After Inclusive Pedagogies

Source: Author's data presentation (2025)

CHAPTER 3: METHODOLOGY

This study employed a qualitative research design complemented by descriptive statistics. Data was collected through document analysis, including reports from CEMASTEIA, UNESCO, and various African ministries of education. Additionally, semi-structured interviews were conducted with ten educators and policy officers from Kenya, Rwanda, and Malawi. Analytical techniques included thematic analysis for qualitative data and basic descriptive statistics for quantitative trends. Data visualizations such as bar charts and pie charts were used to highlight findings on mentorship program outcomes and inclusive pedagogical impacts.

CHAPTER 4: DATA PRESENTATION, ANALYSIS AND DISCUSSION

4.1 Policy Reforms

Table 1: Policy Reforms

Country	Gender-Inclusive Policy	STEM	Increase in Female STEM Enrollment (%)
Kenya	Yes		35%
Rwanda	Yes		42%
Uganda	Partial		18%
Nigeria	No		10%
South Africa	Yes		38%

4.2 Mentorship Programs

A bar chart shows the impact of five mentorship programs in Kenya on female STEM career uptake. Participants were three times more likely to pursue STEM careers. Challenges include scalability and access in rural areas.

4.3 Inclusive Pedagogies

A pie chart representing classroom participation by gender after introducing inclusive pedagogies shows a shift from 40% girls and 60% boys to 60% girls and 40% boys. Teacher feedback supports improved engagement and learner confidence.

4.4: Discussion

While policy reforms set the foundation, mentorship, and pedagogy directly affect learner experience. A multi-pronged approach ensures systemic transformation. Effective collaboration between government, schools, and NGOs is essential.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.0: Conclusion

Empowering women and girls in STEM requires removing systemic barriers through targeted policy, mentorship, and inclusive pedagogy. Such efforts must align with broader developmental goals under Agenda 2063.

5.1: Recommendations

1. Strengthen implementation and monitoring of gender-inclusive STEM policies.
2. Expand access to mentorship programs, especially in rural communities.
3. Train educators on inclusive pedagogies and integrate gender responsiveness into teacher training curricula.
4. Foster public-private partnerships to support women-led STEM initiatives.

Empowering Women and Girls' Participation in Science, Technology, Engineering, and

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ARTICLE 11

Uncovering Children's Abilities: A Case Study of Competence Development through Home-Linked Chores in an Early Learning Classroom

Masuzyo Sibande ¹, Chipso Namakau Sakala ²,

¹masuzyosibande@yahoo.com, ²chipsonamakau@gmail.com

¹North rise Primary School, Ndola, Zambia

²Ministry of Education, Directorate of National Science Centre

ABSTRACT

This study explored how home-linked chores can serve as meaningful contexts for competence development in early learning classrooms. The purpose was to examine how young children demonstrate and extend their abilities when engaged in familiar, real-life tasks such as washing, sweeping, arranging, and simple cooking. A qualitative case study design was employed within an action-research framework. The target group comprised early childhood learners aged 4–6 years in a pre-primary classroom, with both boys and girls participating in structured practical activities. Parents were indirectly involved as contributors of materials and as post-activity informants, offering insights on their children's engagement. Data were collected through classroom observations, learner interviews, and informal parent discussions. Findings revealed that children exhibited higher levels of independence, initiative, and collaboration than initially expected. Through observation, imitation, and peer learning, learners developed both fine-motor and social competences. Parents reported a positive shift in perception, acknowledging that their children were more capable and responsible than previously assumed. The study concludes that connecting classroom learning to home experiences through chores enhances confidence, creativity, and responsibility in early learners. It recommends that teachers intentionally integrate everyday home tasks into early learning environments to strengthen competence-based education.

Keywords: competence-based learning; early childhood education; experiential learning; home-linked chores; learner independence

1. Background

Competence-Based Education (CBE) in Zambia emphasizes the development of learners' practical, cognitive, and social abilities through active engagement in real-world contexts. In early childhood education, young learners are naturally curious, observant, and eager to imitate adults, making experiential learning a powerful avenue for competence growth. However, many classroom activities remain limited to symbolic play or teacher-led tasks, overlooking opportunities for integrating authentic home experiences into structured learning. Home-linked chores such as sweeping, washing, cooking, or organizing offer culturally relevant, low-cost, and developmentally appropriate experiences that foster autonomy and responsibility. In many Zambian homes, children are often shielded from such tasks under the perception that they are too young or that chores are burdensome. This study therefore sought to explore how introducing familiar home activities within the classroom can uncover children's hidden abilities and support competence development under the 2023 revised curriculum's emphasis on life skills and learner agency.

2. Purpose of the Study

The purpose of this study was to examine how participation in home-linked chores supports competence development among early learners. It aimed to explore the ways in which children demonstrate independence, creativity, and collaboration through familiar tasks adapted for classroom contexts.

3. Objectives

- 1.To identify the types of competences that emerge when children engage in home-linked chores in a classroom environment.
- 2.To document learner behaviors, attitudes, and collaboration patterns during chores and cooking activities.
- 3.To capture parents' reflections on their children's capabilities following classroom engagement in home-linked chores.

3. Literature Review

3.1 Competence-Based Learning in Early Childhood

Competence-Based Education views learning as the acquisition of integrated knowledge, skills, values, and attitudes applied in real-life contexts (Tessmer & Jonassen, 1992). In early years, competences include problem-solving, collaboration, communication, and self-management (European Commission, 2019). Studies in Sub-Saharan Africa indicate that contextual, activity-based learning enhances retention and motivation (Munyeka et al., 2021).

3.2 Experiential and Socio-Constructivist Perspectives

Kolb's (1984) experiential learning cycle concrete experience, reflective observation, abstract conceptualization, and active experimentation explains how children learn through doing. Vygotsky (1978) adds a social dimension, emphasizing that learning occurs within the Zone of Proximal Development through guidance and peer interaction. When learners collaborate on chores or cooking, they internalize new skills within supportive social frameworks.

3.3 Home-Linked Tasks and Life Skills

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Scholars such as Rogoff (2003) and Nsamenang (2012) show that participation in household routines builds early autonomy and cultural competence in African contexts. Integrating such activities into classrooms aligns with UNESCO's (2022) Life Skills Framework and SDG 4, which emphasize practical learning for sustainable living. Chores develop fine-motor coordination, sequencing, hygiene awareness, and teamwork foundational competences for later STEM and vocational learning (Akinyemi & Adeyinka, 2022).

3.4 Bridging Home and School Learning

Epstein's (2018) model of school-family partnerships highlights that meaningful parental engagement enhances learner confidence and achievement. When parents observe competence in familiar domains such as cooking or cleaning, they become partners in reinforcing positive learning behaviors at home.

4. Methodology

4.1 Research Design

The study adopted a **qualitative case study** approach within an **action-research framework**, enabling iterative observation, reflection, and adjustment of classroom practice. This design was appropriate for examining naturally occurring behaviors and teacher reflections in a real-life context.

4.2 Participants and Setting

Participants were **early childhood learners aged 4–6 years** (both boys and girls) in one pre-primary classroom at Northrise Primary School, Ndola. The class was facilitated by the teacher-researcher (Masuzyo Sibande). Parents were indirectly involved by supplying food ingredients and utensils and later reflecting on outcomes.

4.3 Data Collection Procedures

- **Observation:** Continuous classroom observations recorded learner engagement, collaboration, and initiative.
- **Informal Interviews:** Short post-activity conversations with learners captured their feelings and reflections.
- **Parent Discussions:** Casual feedback sessions after activities provided insights into parental perceptions.

4.4 Data Analysis

Data were analyzed thematically using the steps outlined by Braun and Clarke (2006). Transcribed observation notes and interview summaries were repeatedly read, coded, and clustered into themes such as *independence*, *peer collaboration*, and *parental perception*. Triangulation among observations, learner responses, and parental accounts enhanced credibility. Member-checking with the collaborating teacher ensured confirmability of interpretations.

4.5 Ethical Considerations

Parental consent was sought verbally, and learners' identities were anonymized. Activities adhered to safety standards, particularly during cooking sessions, under close teacher supervision.

5. Findings

Analysis of observations and discussions revealed three central themes:

5.1. Emergence of Independence and Responsibility

Learners showed enthusiasm in performing tasks independently. Many insisted on repeating chores until they mastered them. Tasks such as washing and organizing materials enhanced self-regulation and pride in personal accomplishment.

(Insert Photo 1: Learners washing clothes and utensils)

5.2. Peer Learning and Collaboration

Children learned through imitation and social interaction. Some observed peers before trying tasks themselves, consistent with Vygotsky's (1978) concept of social constructivism. Cooperative cooking sessions fostered teamwork and turn-taking.

(Insert Photo 2: Learners collaborating during cooking)

5.3. Transformation in Parental Perceptions

Parents reported being surprised at their children's competence levels. One parent noted, *"I always thought my child was too young to cook, but she fried eggs confidently and insisted on helping at home."* Such feedback indicated that home-linked chores can positively reshape parental attitudes towards child capability.

6. Discussion

The results affirm that competence development in early childhood is strengthened when learning mirrors children's lived realities. Integrating chores and cooking provided **authentic tasks** that merged physical, cognitive, and socio-emotional learning.

Kolb's (1984) experiential model explains how learners moved from **concrete experience** (doing chores) to **reflection** ("I can wash my shirt") and **conceptualization** (understanding cleanliness and order). These cycles cultivated agency and problem-solving—cornerstones of competence-based education.

Peer interaction observed in this study echoes Vygotsky's (1978) notion that knowledge is co-constructed. By watching and imitating, children operated within their *Zone of Proximal*

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Development, gradually achieving mastery. Similar outcomes were documented by Blatchford et al. (2011), who found that cooperative learning fosters engagement even in large classes.

Furthermore, the finding that parents re-evaluated their children's abilities aligns with Epstein's (2018) parent-school partnership theory, reinforcing that competence development extends beyond the classroom. When parents witness competence in daily life tasks, home reinforcement becomes more consistent, enhancing sustainability of learning outcomes.

From a cultural standpoint, the study supports Nsamenang's (2012) argument that African child-rearing traditions inherently value *learning by participation*. Integrating such traditions into formal education contextualizes the curriculum and affirms local knowledge systems.

Overall, the study illustrates that competence development is **not a function of age or academic content**, but of opportunity, environment, and belief in children's capability. Home-linked chores, therefore, serve as pedagogical tools that blend cultural relevance with CBE goals of creativity, responsibility, and collaboration.

7. Conclusion

The study concludes that early learners possess greater potential than often assumed and that authentic, home-linked activities can uncover and strengthen diverse competences. By engaging in

chores such as washing, organizing, and simple cooking, learners developed independence, fine-motor control, teamwork, and a sense of responsibility. Integrating these experiences into early learning classrooms aligns with Zambia's competence-based reform agenda, nurturing lifelong learning habits from the foundational years. Teachers should embrace experiential, low-cost, culturally grounded strategies that position the classroom as an extension of the home.

8. Recommendations

1. **Curriculum Integration:** Teachers should embed home-linked chores into early learning schemes to contextualize competence development.
2. **Teacher Reflection:** Educators should continuously observe and document learner growth through experiential activities.
3. **Parent Engagement:** Schools should engage parents in collaborative dialogue to harmonize home and school learning experiences.
4. **Policy Support:** Curriculum developers should emphasize local, life-oriented competences within Zambia's CBE framework.

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ARTICLE 12

Preliminary findings from piloting low-cost engineering and robotics in 7 STEM high schools in Ghana

Isaac Sogbadzi¹, Daniel Ewusi-Essel¹, Mawuena Asem-Hanson¹ and Heather Beem^{1,2}
isogbadzi@practicaleducationnetwork.com, dewusi-essel@practicaleducationnetwork.com, mahanson@practicaleducationnetwork.com, heather@practicaleducationnetwork.com

¹Practical Education Network, Ghana

²Ashesi University, Ghana

ABSTRACT

Ghana's National Council for Curriculum and Assessment (NaCCA) in 2023 introduced a new STEM curriculum for its Senior High and Senior High Technical Schools. While this was a bold step, some SHS teachers felt underequipped to use the curriculum. Practical Education Network's work with 25 teachers across seven STEM schools piloting the new engineering and robotics curricula provides the basis for this paper. In November 2023, the government organized a two-week training at KNUST, followed by a year-long PEN-led coaching and mentoring on hands-on learning with low-cost, locally-available materials.

Pre- and post-surveys showed gains in 13 of 14 competencies. Highly significant improvements ($p < 0.001$) occurred in schematic symbols

(0.94), CAD (1.71), rapid prototyping (2.00), microcontroller programming (1.59), and reading microcontroller data (1.47).

Significant gains ($0.001 \leq p < 0.05$) were seen in ethics/safety (0.94),

identifying components (0.88), LED polarity (0.53), resistors (0.71),

voltage vs. current (0.94), multimeter use (1.24), digital vs. analog

(1.06), and flowcharts/logic (0.94). Engineering basics (0.59) improved

but was not statistically significant ($p \approx 0.066$). Overall statistical

scores rose from 49.29 to 63.41 ($\Delta = 14.12$; $t \approx 7.94$; $p < 0.00001$; $d \approx 1.92$).

Interviews revealed teachers gained confidence, observed greater student participation, and reported stronger links between lessons and everyday life. Students demonstrated curiosity and applied STEM concepts to practical projects. Leveraging locally-available materials to teach engineering and robotics proved impactful in Ghanaian classrooms, offering a pathway to decolonizing STEM education in Africa.

Keywords: Teacher Training, STEM, Hands-on Learning, Curriculum Implementation, Practical Learning, Decolonizing STEM

1.0 Introduction

The call to decolonize STEM education in Africa has become increasingly urgent. This means shifting away from Eurocentric frameworks and lecture-driven traditions toward approaches that make science and technology meaningful, sustainable, and socially relevant in African classrooms.

In Ghana, this conversation gained new momentum in 2023 when the National Council for Curriculum and Assessment (NaCCA) introduced a new STEM curricula for Senior High and Senior High

Technical Schools under the National Pre-Tertiary Education Curriculum Framework. These reforms emphasized learner-centered, competency-based approaches aimed at equipping students with 21st-century skills (NaCCA, 2023). While this was a bold step in the right direction, many SHS teachers felt underequipped to implement the curricula in under-resourced settings.

This paper draws on the experience of the Practical Education Network (PEN), a Ghana-based NGO, in their work with 25 teachers across seven STEM schools across the country to pilot the new engineering and robotics curricula. The intervention began in November 2023 with a two-week in-person training workshop at the Kwame Nkrumah University of Science and Technology (KNUST), followed by a year of structured coaching and mentoring. PEN's curriculum and training officers visited schools twice a month, helping teachers translate abstract concepts into practical lessons using low-cost, locally available materials.

2.0 Literature Review

The discourse on STEM education has evolved significantly over the past two decades, with an increasing emphasis on aligning curricula with global competencies, decolonising knowledge frameworks, and preparing teachers to deliver contextually relevant pedagogy. Internationally, initiatives such as the Next Generation Science Standards (NGSS Lead States, 2013) and Bybee's (2013) arguments for STEM education highlight the critical need to promote inquiry-based learning, problem-solving, and innovation in ways that align with 21st-century demands. These frameworks emphasize interdisciplinarity and future readiness, although they have been largely grounded in Western existing traditions.

Within Africa, regional strategies have sought to contextualise STEM within local realities. The Continental Education Strategy for Africa 2016–2025 (CESA 16-25) African Union, (2016) positions STEM as central to socioeconomic transformation, underscoring the importance of teacher capacity-building and curriculum alignment to sustainable development. Similarly, the National Pre-Tertiary Education Curriculum Framework developed by Ghana's NaCCA (2020) incorporates competency-based approaches, yet implementation challenges persist, particularly in rural and low-resource schools where teacher preparation is limited.

A growing body of scholarship has raised concerns about the dominance of Eurocentric perspectives in STEM education. Le Grange (2016) notes that decolonising curriculum involves broadening the scope of knowledge systems to include locally grounded approaches. Shabalala (2025) shows how bringing indigenous knowledge into environmental education can make learning more relevant and sustainable in African contexts. Likewise, Kiggundu and Mavhunga (2022) argue that without African perspectives, STEM risks reinforcing existing inequalities rather than addressing them. Porter and Siddiqui (2024) also caution that STEM education can unintentionally reproduce colonial or militarised themes, calling for pedagogies that encourage more critical and inclusive approaches.

Global policy frameworks provide a unifying vision for these reforms. The Incheon Declaration and Framework for Action (UNESCO, 2015) explicitly situates STEM within Sustainable Development Goal 4, advocating for inclusive, equitable, and quality education. This agenda compels nations to balance global benchmarks of STEM excellence with localised strategies that reflect cultural, historical, and socioeconomic contexts.

Sebsibe and Abegaz (2025) highlight that STEM education in Africa continues to face systemic barriers, particularly in terms of teacher preparation, learning resources, and equitable access. Yet, they argue that STEM remains central to national development and future skills, echoing the African Union's CESA 16–25 agenda.

Recent Ghana-focused studies and policy documents reinforce the need for context-sensitive STEM reforms that combine curriculum change with substantial teacher professional development and locally relevant knowledge systems. The National Pre-Tertiary Education Curriculum Framework (NaCCA, 2020) explicitly foregrounds competency-based approaches and calls for teacher capacity-building to deliver inquiry-led and contextually relevant learning. Empirical work in Ghana shows persistent gaps between curriculum intentions and classroom practice. For example, *Investigating STEM Teachers' Personal and Sociocultural Particularities in the Ghanaian Context* (Anning, 2024) found that teachers' beliefs, background, and school environment strongly influence how well they can enact competency-based STEM teaching, especially in rural and under-resourced schools. Field interventions also illustrate promise.

PEN's workshops in Accra and beyond have demonstrated improvements in teacher confidence and uptake of hands-on activities with locally available materials aligned with the Ghanaian STEM curriculum (Practical Education Network, 2018). Moreover, work by Gyamerah (2024) resulted in a co-created pedagogical guide to integrate indigenous knowledge systems into science and mathematics teaching, which is now being adopted by teachers in multiple regions (Gyamerah, 2025). Recent policy workshops (IERIS-UEW and SACOST, 2024) have also called for official curricula to better integrate indigenous perspectives to enhance cultural identity, equity, and global citizenship (Mereku, 2024). Together, these Ghanaian policy and research sources suggest that scalable teacher-development models, aligned to NaCCA and grounded in local contexts and indigenous knowledge, are critical for translating decolonized STEM aspirations into classroom realities.

Several literature, as shown in this session, underscores that advancing STEM education in Africa requires curriculum reform and demands a systemic approach that combines decolonised knowledge frameworks, teacher professional development, and policy coherence. By situating STEM education within both global discourses and African existing traditions, it is possible to chart a path towards a scalable framework for teacher professional development in low-resource countries.

3.0 Methodology

This study employed a convergent parallel mixed-methods design to assess PEN's STEM coaching and mentoring program. Quantitative and qualitative data were collected together, analyzed separately, and integrated during interpretation to provide a holistic understanding of program implementation and effectiveness. The research process followed three phases: a pre-intervention baseline assessment (February–June 2024), an intervention phase (May–September 2024), and a post-intervention monitoring and evaluation phase (November 2024).

The study was situated within the Government of Ghana's broader STEM transformation agenda, supported by Transforming Teaching, Education & Learning (T-TEL), a Ghanaian NGO. PEN implemented the intervention in seven Senior High Schools (Abomosu STEM, Accra High, Awaso STEM, Bosomtwe Boys, Bosomtwe Girls, Koase STEM, and Kpasenkpe STEM) across six regions, representing diverse socio-economic and geographic contexts. A key contextual factor was the

establishment of new robotics and engineering laboratories, with PEN collaborating with T-TEL and Aenics Engineering Limited to build teacher capacity to effectively use these STEM Labs through a two-week in-person workshop after the coaching session had ended. Because Koase STEM Senior High did not have any representatives at the initial workshop organized in November 2023, PEN's mentoring and coaching session became the primary source of professional development in implementing the new curriculum.

25 STEM teachers participated, 24 males and 1 female. This highlighted the persistent underrepresentation of women in STEM teaching, underscoring the importance of promoting gender equity in future recruitment and professional development efforts. 96% of these teachers were early in their careers. Students and school leaders were also sampled for semi-structured interviews. Students comprised first-year engineering cohorts (average class size 55; approx. 250 per school).

The intervention was a multi-component coaching program guided by two roadmaps (engineering and robotics). Coaches visited each school twice monthly, spending two working days per visit. Coaching cycles included baseline assessment, classroom observations, co-creation of content for subsequent meetings, technical training, and feedback. Pedagogies emphasized inquiry-based, kinesthetic, and problem-solving approaches, while technical modules spanned ethics and safety, circuits, renewable energy, engineering design, prototyping, Arduino programming, automation, robotics, sensors, and 3D modeling. The program culminated in a two-week residential workshop in one of the new labs to familiarize teachers further with the lab equipment for the various schools.

Data collection employed multiple methods for triangulation. Quantitatively, teachers completed pre- and post-training self-assessments (5-point Likert scale across 14 domains; 25 pre, 19 matched pairs post), serving as the primary measure of self-efficacy. Qualitatively, semi-structured interviews were conducted with teachers and school leaders to capture their perceptions of the coaching process, challenges of implementation, and its impact on teaching practice. Semi-structured interviews were selected because they balanced consistency across participants with flexibility to probe deeper into emerging issues. Additional interviews with students explored their experiences of engagement, motivation, and innovation.

Data analysis followed two strands. Quantitative data were analyzed in SPSS (v28) using descriptive statistics, paired-sample t-tests, and effect sizes (Cohen's *d*). Quotes were obtained from the semi-structured interviews..

4.0 Findings

The needs assessment during the pre-coaching phase revealed that while many teachers held engineering-related degrees, they had limited prior exposure to hands-on technical training in areas such as soldering, electronics, microcontroller programming, 3D modeling, and inquiry-based pedagogy.

A paired-sample t-test of matched participants ($n=19$) revealed a significant increase in self-rated competency across all 14 domains on a scale of 1-5, with mean total scores rising from 49.29 (pre-coaching) to 63.41 (post-coaching), representing a mean difference of +14.12 ($T(16) = 7.94$, $p < .00001$). The effect size was large (Cohen's $d = 1.92$). The degree of freedom (T) was 16 because 2 responses were discarded because they could not be matched to their pre-coaching survey data, making $(n-1) = 16$.

Competency Area	Mean Gain (Δ)	Cohen's d	Effect Size Interpretation
Rapid Prototyping	+2.00	1.57	Large
CAD Experience	+1.71	1.26	Large
Reading Data from Microcontrollers	+1.47	1.19	Large
Schematic Symbols (Interpretation)	+0.94	1.14	Large
Microcontroller Programming	+1.59	1.03	Large
Use of Multimeter	+1.24	0.95	Large
Voltage vs Current	+0.94	0.82	Large
Flowcharts & Logic	+0.95	0.79	Medium
Identify Components	+0.88	0.79	Medium
Ethics & Safety	+0.94	0.75	Medium
Digital vs Analog	+1.06	0.68	Medium
LED Polarity	+0.53	0.56	Medium
Resistor Use	+0.71	0.56	Medium
Engineering Principles	+0.59	0.48	Medium

Table1: Practical significance of gains (Effect size)

Table 1 depicts consistently large effect sizes across technical and professional domains, underscoring that the observed improvements were both statistically significant as well as educationally meaningful. The largest gains were in technical skills: Rapid Prototyping (+2.00, $d = 1.57$), Computer Aided Design (CAD) (+1.71, $d = 1.26$), Microcontroller Programming (+1.59, $d = 1.03$), and Reading Data from Microcontrollers (+1.47, $d = 1.19$). Significant improvements also occurred in core engineering practices, including Using a Multimeter (+1.24, $d = 0.95$), Interpreting Schematics (+0.94, $d = 1.14$), Identifying Components (+0.88, $d = 0.79$), and Differentiating Voltage & Current (+0.94, $d = 0.82$). Professional competencies such as Ethical and Safety Protocols also improved (+0.94, $d = 0.75$).

A large majority of teachers (79%) reported significant improvements in their pedagogical approaches. Quantitative results reinforced this. Teachers' self-efficacy scores rose by an average of +14.12 points ($p < .00001$, $d = 1.92$), with notable gains in technical competencies such as microcontroller programming (+1.59) and CAD (+1.71).

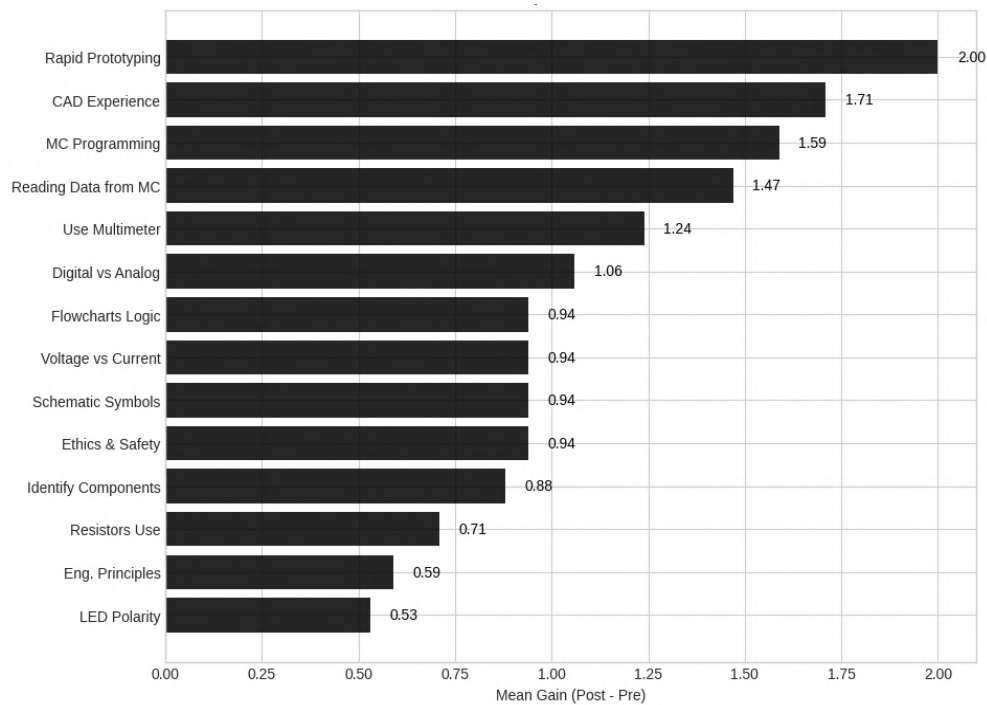


Figure 2 : Teacher competency gains from PEN's Coaching Program

The bar chart in Figure 2 highlights the clear ranking of competency gains, with hands-on technical skills showing the greatest improvements, reflecting the practical emphasis of the program.

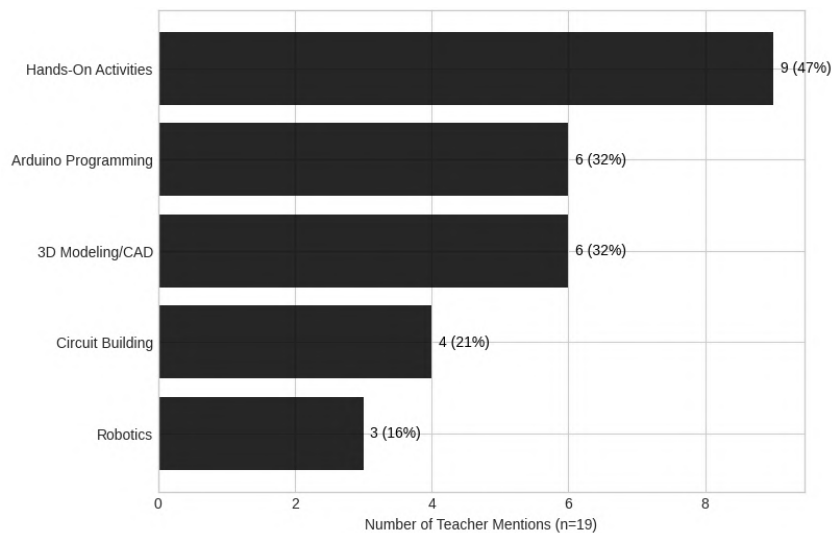


Figure 3: Most Valued Aspects of the Training

Figure 3 shows that teachers valued practical skills above all areas, with hands-on activities, Arduino programming, and CAD modeling mentioned most frequently as the most useful elements of the training.

Survey data from teachers showed a clear shift from theory-heavy instruction to hands-on, problem-based learning. As one teacher from Awaso reflected, *“This program has been an eye-opener. I used to teach with chalk and talk, but now my students are building and experimenting.”* Another teacher described the training as *“a real training college for us, not just a workshop”* (teacher from Kpasenkpe STEM). Even non-engineering specialists embraced engineering content: *“I am a chemistry teacher, but now I can confidently guide my students in robotics and engineering”* (teacher from Bosomtwe Girls STEM).

Teachers also observed dramatic increases in student engagement. *“My students now build after class. Some have won robotics competitions already”* (teacher from Awaso STEM). Students demonstrated critical thinking and innovation, creating solutions tailored to local needs, *“my solar-powered bus will reduce carbon emissions”* (Engineering student from Kpasenkpe STEM).



Figure 4: A teacher at Bosomtwe Girls' SHS programs a servo motor for a robotic vehicle.



Figure 5: A student demonstrates a bionic arm built from cardboard and strings.

All teachers (100%) observed dramatic increases in student engagement and motivation. Learners were described as more curious, enthusiastic, and eager to continue projects beyond the classroom. Some purchased their own components, while others participated successfully in robotics competitions. Semi-structured interviews confirmed that students increasingly viewed STEM as both “enjoyable” and “relevant to solving real-world problems.” Teachers shared examples of innovation, including a bionic arm designed for individuals with gripping difficulties and a solar-powered bus model.

Logistical challenges were also reported by 37% of teachers. These included limited classroom space, coaching sessions conflicting with school timetables, and unreliable internet connectivity in some regions. Some teachers suggested weekend or vacation sessions as an addition to regular activities: *“If this were done during vacations in addition to the regular session we are having, it would be easier for both teachers and students to learn more”* (teacher from Abomosu STEM).

4.1 Discussion

The findings present a case for the effectiveness of PEN’s coaching program. The statistical evidence indicates progress against the measured competencies. The paired-sample t-test revealed a mean increase of +14.12 points in self-rated competency, with a large effect size (Cohen’s $d = 1.92$). According to benchmarks (Cohen, 1988), an effect size above 0.8 is already considered large; thus, $d = 1.92$ signals a transformation of systemic magnitude.

The results underscore that these gains were consistently large across both technical and pedagogical domains. Another insight from the large effect sizes showed that teachers did not only score higher on a survey of self-efficacy, but actually underwent meaningful learning. For example, it was the technical skills areas such as Rapid Prototyping (+2.00, $d = 1.57$), CAD (+1.71, $d = 1.26$), and Microcontroller Programming (+1.59, $d = 1.03$), that saw the biggest improvements. The sharp gains reflect the program’s effectiveness in addressing the weakest baseline competencies and building new technical skills that they previously lacked.

The results again show the ranking of competency gains, showing that hands-on technical skills advanced more sharply than other areas. This aligns with the qualitative accounts of teachers moving from “chalk-and-talk” to practice-based teaching. The data shows that the PEN model directly filled the gap in applied engineering fields. In other words, the largest improvements are concentrated in the skills that were previously the weakest.

The study reveals what teachers themselves valued most. 47% cited hands-on activities, 32% highlighted Arduino programming, and another 32% pointed to CAD modeling as the most valuable aspects of the training. This convergence of teacher preferences with the areas showing the strongest quantitative gains provides an important validation. It demonstrates that the program’s most impactful components were also the most meaningful to teachers, making it both statistically robust as well as practically and professionally relevant.

The universal reporting of increased student engagement from 100% of teachers indicates that the benefits of the coaching program extended beyond the teachers themselves and into the classroom.

Teachers’ qualitative reports of students sustaining projects outside class, and competing successfully in robotics competitions are direct manifestations of the technical competence gains observed in the students. This suggests that when teachers gain technical and practical capacity, students also reap positive results.

Semi-structured interviews with students also showed that learners are seeing the new changes in their classrooms and are already enjoying hands-on learning. This is deepening their understanding in engineering and robotics and is pushing many of them to choose STEM-related careers after their Senior High School education. This highlights the long-term benefits of student-centered learning and hands-on teaching with locally available materials, which were the core of the whole coaching program.

All together, the data paints a picture of promise. The coaching model has proven highly effective at equipping teachers with technical and pedagogical competencies (large effect sizes across domains), aligning teacher values with actual skill gains and creating changes in student learning and engagement. However, for these outcomes to scale sustainably, systemic investment is essential. The findings signal the success of the PEN model and also its policy relevance in driving transformation in STEM education in Ghana and across the region.

5.0 Conclusion

This study shows the results from PENs coaching model using locally available materials and hands-on pedagogies. This is a step in the right direction in decolonizing STEM pedagogy in Ghana and beyond. Through the coaching program, teachers in seven STEM schools across Ghana grew in confidence and competence, shifting from theory-heavy lessons to hands-on, problem-solving approaches using local materials. The numbers confirmed it, and so did the stories. Classrooms became places where students were curious, engaged, and building real prototypes that addressed local challenges.

The message for policymakers and practitioners is that sustained, practice-based coaching works, and will be necessary if embedded into national frameworks. For development partners, this is an

invitation to back human capacity with support so that teachers can fully bring their new skills to life.

Looking ahead, more research is needed to understand how these gains hold up over time, how they affect exam performance and innovation, and whether this model can be adapted to other African contexts.

When teachers are equipped and encouraged to teach in ways that connect with their realities, STEM classrooms can become incubators of creativity and innovation. The PEN coaching program is a reminder that African-grown solutions can lead the way in transforming education and in shaping a generation of problem-solvers who see themselves not just as learners, but as creators of solutions for their communities.

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APPENDIX

Appendix A: Pre - Coaching and Post Coaching Survey Instrument

Section 1: General Information

- 1.Full Name
- 2.School Name
- 3.What are your expectations for the Teacher Coaching Program?
- 4.Do you have any prior experience with the following? (Select all that apply)
 - Robotics Education ○ Engineering Education ○ None

Section 2: Self-Assessment of Engineering and Pedagogical Competencies

(Scale: 1 = Novice, 5 = Expert)

- 5.How confident are you in explaining the basic principles of engineering and how they are used in everyday objects?

How comfortable are you in identifying ethical considerations and safety protocols in engineering practices? 6.How well can you identify basic electrical components physically?

- 7.Can you easily identify the positive and negative legs of an LED bulb?
- 8.Do you understand how and why resistors are used in circuits?
- 9.Can you identify basic symbols of components in a simple schematic diagram and replicate it using real components?
- 10.How well can you differentiate between voltage and current in a circuit?
- 11.How comfortable are you using a multimeter to measure voltage, current, and resistance?
- 12.Have you ever used any Computer-Aided Design (CAD) software for creating 3D models?
- 13.Are you familiar with different rapid prototyping techniques (e.g., 3D printing, casting, PCB fabrication, laser cutting)?
- 14.Have you ever programmed a microcontroller (e.g., Arduino)?
- 15.Can you identify and differentiate between digital and analog signals?
- 16.How comfortable are you with reading data from a microcontroller (e.g., temperature sensor reading) using a computer program?
- 17.How comfortable are you using flowcharts to represent the logic and decision-making steps within a simple program?

Section 3: Overall Confidence

19. In conclusion, how confident are you in your ability to teach engineering concepts?
 - Not Confident at All ● Somewhat Unsure ● Neutral ● Somewhat Confident ● Very Confident

Section 4 - Only for Post Survey

What aspects of the training sessions did you find most valuable?

What could be improved in future training programs?

Did you observe any changes in your students' engagement and learning after implementing the strategies learned during the coaching program? (Please elaborate) Were there any specific challenges you encountered while implementing the coaching program strategies? If so, please explain.

What are your suggestions for improving the SHS STEM Teacher Coaching Program in the future?

ARTICLE 13

Sustaining the Ripple Effect: Educators' Cascading of Foundational Learning Environments following KCCP 2025

Chipo Namakau Sakala and Natasha R Nyangwete

chiponamakau@gmail.com, nnyangwete@gmail.com,

Ministry of Education, Directorate of National Science Centre

Kaleya West Combined School, Mazabuka

ABSTRACT

The purpose of this study was to examine how educators who participated in the Knowledge Co-Creation Programme (KCCP) 2025 sustained and cascaded the theme of Foundational Learning Environments within their local contexts. It sought to understand the extent of implementation, the strategies used, and the emerging impact on teaching and learning practices in participating countries. A descriptive qualitative design was employed, focusing on post-training reflections and activity reports submitted by KCCP 2025 alumni. The target group comprised educators from 14 African countries, with reports received from all fourteen representatives and nine (9) countries indicating active cascading of the Foundational Learning Environment theme. Data were collected through document analysis of post-training reports, which provided evidence of outreach activities, school-based workshops, and educator-led innovations. Thematic analysis identified common patterns, variations, and success indicators on the type of cascade activity conducted across different country contexts. Results revealed that educators successfully cascaded training concepts through structured in-service sessions, peer-learning communities, and integration of learner-centered pedagogies, while others focused on developing foundational learning environments through the creation and redesigned learning spaces that enhanced inclusivity, visibility of learning outcomes, and hands-on engagement. These cascaded activities demonstrated how the training concept of developing learning environments was localized and operationalized by educators in their country settings. The findings suggest that international professional development programmes like KCCP can generate sustainable transformation when participants are supported to contextualize, disseminate, and integrate competences that embed the culture of co-creation and innovation in African education systems.

Keywords: Foundational learning, Learning environments; Knowledge Co-Creation Programme; cascading; competence-based education; foundational learning environments

1. Introduction

Sustaining the Ripple Effect: Educators' Cascading of Foundational Learning Environments

The Knowledge Co-Creation Programme (KCCP), supported by international collaboration and hosted in Zambia, serves as a professional learning platform aimed at strengthening Science, Technology, Engineering, and Mathematics (STEM) education across Africa. The 2025 theme, *Foundational Learning Environments*, sought to help educators understand how learning spaces—physical, psychological, social, and technological—can influence competence acquisition. Post-training expectations encouraged participants to cascade the acquired skills to colleagues and learners in their home countries, thereby sustaining a “ripple effect” of innovation. The concept of cascading aligns with peer-to-peer professional development, where trained educators serve as change agents for

contextualized curriculum implementation. This study examines the scope and nature of these cascading efforts across participating countries.

2. Statement of the Problem

While international training programmes such as KCCP provide opportunities for skill development, the sustainability of their impact depends on whether participants apply and disseminate the learned practices after returning home. In many African education systems, post-training follow-up and documentation of cascading practices remain limited. Without empirical evidence of implementation, the long-term value of such initiatives cannot be ascertained. This study therefore sought to investigate how KCCP 2025 alumni sustained and cascaded the theme of Foundational Learning Environments, identifying practical activities, successes, and challenges encountered in translating training into practice.

3. Literature Review

The concept of foundational learning environments is rooted in constructivist and competence-based education theories, which emphasize that learning occurs through interaction, collaboration, and contextual engagement (Biggs & Tang, 2011). Studies by Hofstein and Lunetta (2004) and Baird et al. (2017) underscore the role of practical learning spaces in fostering scientific inquiry and problem-solving skills. In African contexts, the shift from outcome-based to competence-based education highlights the need for adaptable environments that nurture creativity, inclusivity, and learner agency (Anh et al., 2024). Professional development programmes that emphasize co-creation and peer exchange—like KCCP—mirror the model of “communities of practice” (Wenger, 1998), promoting continuous reflection and adaptation. However, the extent to which international training translates into local innovation remains under-documented. This study contributes to filling this gap by examining post-training cascading experiences across multiple African nations.

4. Purpose and Significance of the Study

The purpose of this research was to assess how educators who participated in the **KCCP 2025** sustained and cascaded the **Foundational Learning Environment** theme in their home institutions and communities. This study is significant as it documents how international professional learning initiatives can catalyze localized educational reform. It provides evidence that KCCP alumni are not passive recipients but active disseminators of pedagogical innovation. The research offers insights to ministries of education, donors, and training agencies on how to track, support, and scale the impact of professional development beyond the training venue.

5. Objective of the Study

The objective of the study was; To determine the extent of cascading activities undertaken by educators following KCCP 2025.

6. Research Questions

The research question guiding this study was; To what extent did KCCP 2025 participants cascade foundational learning environment practices in their respective countries?

7. Methodology

A descriptive qualitative research design was adopted. The target group comprised 14 educators and policymakers drawn from 13 African countries who participated in the KCCP 2025 training. Data collection involved document analysis of post-training reports submitted by participants, focusing on activities conducted to cascade training content. The reports described workshops, peer-learning activities, classroom innovations, and curriculum integration efforts. Thematic analysis was used to identify common strategies, examples, and outcomes across contexts, using codes derived from the study objectives.

8. Results

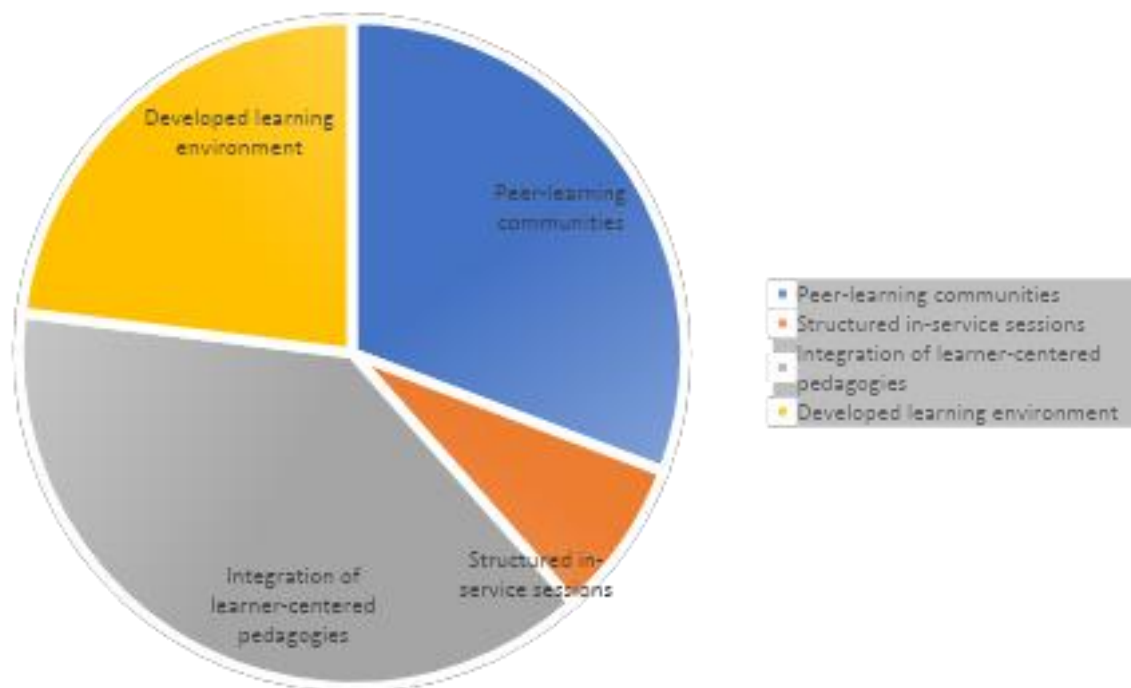
The analysis of cascading activities undertaken by educators following the Knowledge Co-Creation Programme (KCCP) 2025 reveals four dominant strands of implementation that characterize how the theme of Foundational Learning Environments was localized across participating countries. These activity types—peer-learning communities, structured in-service sessions, integration of learner-centered pedagogies, and development of physical learning environments represent diverse yet complementary approaches to sustaining the impact of professional development. Each activity type demonstrates educators' agency in contextualizing the training outcomes to suit their institutional realities. Peer-learning communities emerged as the most widespread strategy, fostering collaborative professional growth and continuous reflection among teachers. Integration of learner-centered pedagogies highlighted shifts in instructional practice toward competence-based education, emphasizing learner engagement and creativity. The development of physical learning environments reflected tangible transformation of classroom spaces, showcasing innovation using local materials and community participation. Meanwhile, structured in-service sessions signified formalized institutional efforts to scale training benefits to larger teacher populations. Collectively, these cascading activities illustrate a robust and multi-dimensional ripple effect of the KCCP 2025, where professional learning translated into visible educational transformation across Africa.

Activity Type	Number of Countries
Peer-learning communities	4
Structured in-service sessions	1
Integration of learner-centered pedagogies	5
Developed learning environment	3

Graphically the pie chart below illustrates this

N

Proportion of Cascading Activity Types



The pie charts showing the distribution of cascading activities across the 13 participating African countries from the KCCP 2025 post-training reports. This illustrates that peer-learning communities and integration of learner-centered pedagogies were the most common cascading strategies, while structured in-service sessions and development of learning environments followed as significant but less frequent approaches.

Summary of Cascading Activities

Nine countries reported active cascading through peer-learning communities, in-service training, and environmental redesign. Peer-learning communities fostered collaborative inquiry and teacher-to-teacher support. Integration of learner-centered pedagogies enhanced classroom engagement and creativity. Developed learning environments demonstrated tangible transformation in school spaces.

Cascading Activities and Examples of Implementation

This section describes the cascading activities undertaken by participants after the Knowledge Co-Creation Programme, together with examples of how each was implemented. Where photographs were provided, they are shown beneath the relevant description; where evidence was submitted as a report or video, this is noted in the text.

Code 1

Under Code 1, the cascading activities focused on developing the learning environment and integrating learner-centred pedagogies. Model outdoor learning spaces were created using recycled materials, and teacher mentoring sessions on inquiry-based learning were conducted. Learner-centred pedagogies were further integrated through culturally contextual learning using storytelling, and a report on this activity was submitted. Through peer-learning communities, the experience was also shared with relevant stakeholders at Ministry Headquarters, for which a further report was submitted.



Figure 1: Learning environment developed under Code 1, including learners using improvised stoves and outdoor play equipment made from recycled materials.

Code 2

Under Code 2, the cascading took place through peer-learning communities. The KCCP experience was shared with school-level management, and plans were made to develop the physical learning space.



Figure 2: Sharing session with school-level management under Code 2.

Code 3

Under Code 3, learner-centred pedagogies were integrated by introducing practical classroom demonstrations that used local materials for science instruction. Videos of these demonstrations were submitted as evidence.

Code 4

Under Code 4, peer-learning communities and learner-centred pedagogies were promoted by organising district peer circles and piloting learner portfolios to assess the growth of competences. Learning environments were also developed. Videos documenting both activities were submitted.

Code 5

Under Code 5, peer-learning communities and learner-centred pedagogies were advanced through workshops that engaged over 200 teachers on active learning methods.



Figure 3: Teacher workshops on active learning methods under Code 5.

Code 6

Under Code 6, the participant used peer-learning communities to share what had been done during the KCCP training in Zambia.



Figure 4: Sharing of the KCCP training experience under Code 6.

Code 7

Under Code 7, the learning environment was developed by constructing low-cost learning centres with science corners, with active participation from the community.



Figure 5: Construction of low-cost learning centres with learner and community participation under Code 7.

Code 8

Under Code 8, structured in-service sessions were held in the form of zonal teacher workshops on competence-based pedagogy, reaching 400 teachers. A report on these workshops was submitted.

Code 9

Under Code 9, the learning environment was developed by revamping laboratories into competence-based learning hubs, and lesson-study groups were launched to strengthen learner-centred pedagogies. Structured in-service sessions were also conducted through zonal teacher workshops on competence-based pedagogy. Following these sessions, some participants trialled the pedagogies in their own classrooms.



Figure 6: Competence-based learning hubs and zonal teacher workshops under Code 9.



Figure 7: Participants trialling the pedagogies in their classrooms and school grounds under Code 9.

9. Discussion

The results of this study illuminate the multifaceted ways in which educators across Africa cascaded the concept of *Foundational Learning Environments* after participating in the KCCP 2025. The four dominant strands peer-learning communities, structured in-service sessions, integration of learner-centered pedagogies, and the development of physical learning environments represent an evolving ecology of professional learning deeply embedded within teachers' local contexts.

The prominence of **peer-learning communities** emphasises the enduring value of collective reflection and collaborative inquiry in teacher development. This aligns with Wenger's (1998) theory of *Communities of Practice*, which positions learning as a socially constructed process wherein knowledge is co-created through interaction and shared experience. By initiating and sustaining these communities, educators not only reinforced their own professional growth but also contributed to a self-regenerating system of support that reduces dependence on external facilitators. The organic nature of these groups highlights teachers' agency and ownership—critical enablers of long-term pedagogical reform.

The **integration of learner-centered pedagogies** across classrooms signifies a paradigmatic shift from content transmission toward competence-based, experiential learning. Educators demonstrated an understanding that foundational learning thrives when learners are engaged as active participants in constructing meaning. This observation aligns with Biggs and Tang's (2011) *constructive alignment* model, where learning outcomes, activities, and assessments are coherently linked to foster deep understanding. The inclusion of local cultural materials and inquiry-driven approaches also reflects a move toward contextualized pedagogy, making learning both relevant and transformative.

Meanwhile, the **development of physical learning environments** to a larger extent using recycled or locally available materials reveals that professional learning outcomes can manifest in tangible, infrastructural innovation. These physical transformations extend beyond aesthetics; they symbolize a commitment to designing spaces that stimulate curiosity, interaction, and competence development. Such efforts mirror emerging literature (Barrett et al., 2019) emphasizing that the physical environment significantly influences learner engagement and achievement, particularly in resource-constrained settings.

Structured in-service sessions

, though less frequent, played an important institutional role by bridging individual teacher initiatives and systemic implementation. These sessions provided formal platforms through which training concepts could be scaled and standardized. The involvement of ministries and school management in such sessions points to the beginnings of institutionalization an essential condition for policy-to-practice continuity.

Sustaining the Ripple Effect: Educators' Cascading of Foundational Learning Environments

Therefore, while the KCCP model has succeeded in igniting innovation, its long-term impact will depend on reinforcing these grassroots efforts through policy alignment, budgetary prioritization, and cross-country mentorship networks.

11. Conclusion

The cascading of foundational learning environments following the KCCP 2025 represents a remarkable instance of professional knowledge transfer and transformation across Africa. Educators not only replicated the principles acquired during training but reimagined them within their unique cultural and institutional realities demonstrating adaptive professionalism and innovative resilience. Through peer-learning communities, learner-centered practices, and locally driven environmental redesigns, they have translated theoretical competence-based education into authentic, actionable change.

However, sustaining this momentum requires deliberate institutional commitment. Ministries of Education and teacher-training agencies should formalize peer-learning communities, integrate cascading reports into national quality-assurance frameworks, and establish mechanisms for continuous mentorship. Furthermore, fostering **cross-country learning platforms** both virtual and in-person will amplify the *ripple effect* initiated by KCCP 2025, ensuring that collaborative knowledge creation becomes a norm rather than an exception.

Ultimately, the study affirms that when professional learning is participatory, contextualized, and supported by enabling systems, it can catalyze not only teacher competence but also broader educational transformation. The KCCP 2025 thus stands as a scalable model for embedding competence-based education across Africa through sustainable, locally driven innovation.

12. Recommendations

1. **Institutionalize cascading** as a formal component of teacher professional development within ministries of education.
2. **Provide seed funding** for local implementation of learning environment projects.
3. **Integrate inter and intra monitoring frameworks** that track cascading outcomes over time.
4. **Encourage collaborative research** among alumni to document and publish local innovations.

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ARTICLE 14

Investigating the impact of Hands-On Laboratory Activities on Student Attitudes Towards Biology and Chemistry

Munashe Chakamanga¹, Tanya Dzinemarira² and Tonderai Rusere²

cynthiadzine13@gmail.com, frankchakamanga@gmail.com, chakamangam@staff.msu.ac.zw ¹Department of Applied Biosciences and Biotechnology, Midlands State University, P Bag 9055, Gweru, Zimbabwe

²Department of Food Science and Nutrition

1.0 Introduction

Students' attitude is one of the most important secondary school learning outcomes. Its importance at this level is premised on the fact that career aspirations are formed at this level of education. Attitude is a construct of the affective domain and has received much attention from researchers in the last 40 years (Aiken & Aiken, 1969; Koballa & Crawley, 1985; Koballa, 1988) and is still continuing. Attitude occupies a central position that determines students' disposition towards a particular school subject. Students' attitude motivates them to pursue a particular course of study and continue in their efforts to attain a mastery level in the subject matter. Students' attitude towards a particular school subject is also reflected in the way they manage their perception and behaviour to the content being learnt. Thus, attitudes do not only facilitate learning, they are products of students' learning (Smith *et al.*, 2012). Attitude may refer to the predisposition in responding in a way that is either favourable or unfavourable in relation to a certain attitude object (Oskamp & Schultz, 2005). This attitude object may range from things like biology, biologists, biology lessons, topics taught in school biology, inquiry-based biology laboratory experiments, biology education research, biological weapons, and biotechnology (Cheung, 2011). Two important reasons were adduced for enhancing students' attitude towards science. First, attitude is linked with academic success. Researchers like Bennett, *et al.*, (2001) and Salta and Tzougraki (2004) reported positive correlations between students' attitude and achievement in chemistry. Salta and Tzougraki (2004) reported that the correlation value between students' achievement in and attitude towards chemistry ranges from 0.24 to 0.41. Bennett *et al.*, (2001) reported that the students with less positive attitude towards chemistry had low achievement score in the chemistry examination. Russell and Hollander (1975) also observed that there is a strong relationship between attitude and achievement, but a positive attitude cannot be inferred from achievement alone. They further reasoned that; there is a possibility for a student who has developed a more positive attitude towards a subject to achieve a low score in that subject and vice-versa. This means, attitude can influence achievement, but achievement may not have influence on attitude. As Stark and Gray (1999), submitted, if attitude is given utmost consideration, the much-anticipated change in cognitive domain may be achieved. The other reason for developing students' positive attitude towards science is its ability to predict behaviours (Glasman & Albarracín, 2006; Kelly, 1988). According to Kelly (1998), the preference for biology, chemistry, or physics in schools by British students was predicated on their likeness for that particular subject. Despite receiving enough attention from researchers in the last 40 years or more, the importance of attitude has often been played down in comparison to achievement when it comes to measuring educational outcomes by the society, curriculum planners and teachers. As Stark and Gray (1999)

stated, one of the major responsibilities of the science teachers is to develop students' positive attitude towards science subject.

1.1 Background to the Study

Most elementary schools use textbooks to teach science (when science is taught at all), but hands-on science curricula have become increasingly popular over the last two decades (cite). Hands-on science typically engages students in research activities in the classroom. Complete curricula of hands-on activities have been developed to effectively replace the use of science textbooks in elementary classroom: Full Option Science System (FOSS; Delta Education), developed at the Lawrence Hall for Science (at the University of California, Berkeley), Science and Technology for Children (STC; Carolina Biological Supply Company), developed by the National Science Resources Center (a joint enterprise of the National Academy of Sciences and the Smithsonian Institution), and Insights (Kendall/Hunt). Other curricula offer a combination of textbook and hands-on activities (e.g. Scott Foresman Science). The hands-on activities provide students with opportunities to engage in exploration and sense making with the science content. Researchers on elementary science reform emphasize the need for students to engage in scientific inquiry (Driver *et al.*, 1994; Harlen, 2004). Engaging students in inquiry can provide a powerful learning experience where students not only learn about science content but also gain reasoning and research skills. Students come to understand the nature of scientific problem solving as the pursuit of meaningful questions through the use of procedures that are thoughtfully generated and evaluated (Magnusson & Palincsar, 1995). The hands-on science curricula (e.g. FOSS, Insights) also describe their materials as promoting scientific inquiry. The positive value of science teaching through inquiry is nearly universal in the literature, but the implementation of this pedagogy in classrooms has been problematic. Critics of the reforms have pointed out that the implementation of hands-on curricula can err either on the side of too much or too little guidance. Research on highschool science labs shows that highly structured activities may teach students to simply 'follow the recipe' and result in little meaningful learning of content or research methodology (NRC, 2005). In the other extreme, if teachers provide too little guidance, the activity becomes "discovery learning" which has not been very effective in previous studies (Mayer, 2004). Observations of hands-on science have indicated that some teachers do not fully implement the curriculum as it is designed (Aschbacher & Roth, 2002). Instead, some teachers have the students conduct hands-on activities without the preparation, analysis and reflection that is often called for. Without having detailed knowledge of the actual implementation of the hands-on curricula, it is not possible to tell how much inquiry is happening. Research on the effectiveness of hands-on science curricula tends to show a positive effect for small tightly controlled studies. Studies where researchers closely monitored the curriculum (often involving technology) have resulted in more science learning (Kracjik *et al.*, 1998; Lehrer, Schauble, Carpenter & Penner, 2000; White & Frederiksen, 1998; Young & Lee, 2005). Research in the 1970s and 1980s showed an advantage for hands-on science (Bredderman, 1983; Shymanski, Hedges & Woodworth, 1990). Stohr-Hunt's (1996) analysis of test data and teachers' self-report of hands-on frequency show very small increases in scores for students who had more hands-on experience. More recent studies have looked at hands-on science implementation within a single district. Research from El Centro Schools shows district reading and writing scores improved after the adoption of hands-on science curricula (Amaral, Garrison, & Klentschy, 2002) and that when teachers have professional development in Scaffolded Guided-Inquiry students learning improves (Vanosdall, Klentschy, Hedges & Weisbaum,

2007). Schymansky, Yore & Anderson (2004) report that added professional development for teachers did not lead to gains in science scores or attitudes about science. The use of hands-on curricula continues to expand, but textbook science is still generally treated as the norm. Many elementary teachers or schools choose a third option which is to teach little or no science, choosing instead to focus on math and language skills which are more heavily tested.

Science education in schools faces the challenge of fostering genuine student engagement and positive attitudes. The traditional lecture-centric approaches often fall short in capturing student interest and demonstrating the real-world relevance of scientific concepts. Hands-on learning, particularly through laboratory activities like practicals, offers a potential solution by providing students with active, experiential learning opportunities. This research investigates the extent to which incorporating hands-on laboratory activities can positively influence student attitudes towards biology and chemistry.

1.2 Statement of the Problem

Many consider STEM (science, technology, engineering, and mathematics) education to be a vital engine of creativity and economic competitiveness. Biology and chemistry are fundamental pillars in this area supporting developments in technology, environmental sustainability, and medicine. But the drop in enrollment and bad perceptions pupils sometimes come to have about these fundamental scientific fields (Osborne, Simon, & Collins, 2003) present a constant obstacle within secondary and tertiary education. Many times seeing biology and chemistry as challenging, abstract, and unrelated to their daily lives causes students disengagement, high STEM major attrition rates, and lost opportunity to develop a scientifically literate populace. Fundamental sciences, Biology and Chemistry, not only support several fields but also assume a main role in finding solutions to actual problems in health, agriculture, manufacturing, and the environment. Still, a persistent worry in science education is the continuous drop in pupils' motivation and curiosity toward these topics. Many students see Biology and Chemistry as abstract, content-heavy, and hard to connect to daily life, which often results in unfavorable opinions, disinterest, and low performance. Such attitudes affect the creation of a scientifically literate and competent workforce by greatly influencing students' desire to seek science-related careers.

Often stressing rote learning, fact memorizing, and teacher-centered techniques, conventional science classroom techniques also depend on these elements. Although these techniques could address curriculum material, they often fall short of promoting interest, critical thinking, or favorable affective inclinations toward science. Studies indicate that attitudes toward science are influenced not just by cognitive elements like performance but also by emotional events including pleasure, curiosity, and assessed relevance. Therefore, neglecting the experiential and applied aspects of science education in teaching techniques might unintentionally perpetuate unfavorable beliefs. Including laboratory exercises is one long-standing teaching technique meant to fight against this disengagement. Hands-on, inquiry-based labs are thought to span the distance between theoretical ideas and practical reality, hence promoting conceptual understanding, sparking curiosity, and fostering favorable attitudes (Hofstein & Lunetta, 2004). Notwithstanding this theoretical potential, the real data on how hands-on labs affect student attitudes is scant and conflicting. Neglecting the affective domain—that of attitudes, motivations, and interests of students (Potvin & Hasni, 2014)—many current studies concentrate mostly on cognitive benefits like exam grades. This gap in the literature presents a

significant problem. First, it is unclear which specific aspects of hands-on laboratory activities (e.g., inquiry-based design, collaboration, relevance to real-world issues) are most influential in shaping student attitudes. Many laboratory exercises remain "cookbook-style," where students follow prescribed steps to achieve a known result, potentially doing little to foster genuine interest or a positive attitude. Second, there is a lack of comparative understanding of how these activities differentially impact attitudes towards biology versus chemistry, two disciplines often taught in tandem but with distinct perceptual challenges (e.g., chemistry's mathematical abstraction vs. biology's complex terminology). Finally, most attitude assessments are conducted immediately after an activity, leaving a gap in understanding the long-term or sustained impact of these laboratory experiences on students' scientific dispositions. Hands-on laboratory activities provide an experiential learning environment where students actively engage in scientific processes, apply theoretical concepts, and develop problem-solving skills. By allowing students to manipulate materials, conduct experiments, and observe outcomes firsthand, laboratory experiences have the potential to make science more tangible, meaningful, and enjoyable. Yet, despite growing recognition of their importance, many schools and universities face challenges such as limited resources, insufficiently equipped laboratories, and inadequate integration of practical work into curricula. Consequently, there is still limited empirical evidence, particularly in the local context, regarding the extent to which hands-on laboratory activities can transform student attitudes toward Biology and Chemistry.

Therefore, the problem this dissertation investigates is the lack of rigorous, empirical evidence detailing if, how, and why hands-on laboratory activities specifically influence student attitudes towards biology and chemistry. Without a clearer understanding of this relationship, educators and administrators may continue to invest significant time and resources into laboratory components without maximizing their potential to inspire and engage the next generation of scientists and informed citizens. The problem, therefore, is that while hands-on laboratory activities are theoretically considered effective in enhancing student engagement and attitudes, there remains a gap in understanding their actual impact in educational settings. Without clear evidence, educators may continue relying heavily on traditional teaching methods that risk further alienating students from science. Investigating how laboratory-based learning influences student attitudes towards Biology and Chemistry is essential for informing curriculum design, improving pedagogical practices, and ultimately promoting sustained interest and achievement in science education.

This study will address this problem by systematically implementing and evaluating a series of intentionally designed hands-on laboratory activities to measure their specific impact on student attitudes. The findings will contribute critical insights to science education theory and provide evidence-based recommendations for curriculum design, aiming to transform laboratory sessions from mere requirements into powerful tools for fostering positive and enduring attitudes towards the vital fields of biology and chemistry.

1.3 Justification

The research question on how hands-on laboratory sessions affect the attitude of the students to biology and chemistry is not an important academic endeavor; it is a research requirement that is explained by a convergence of theoretical, practical, and social requirements. The documented drop in student enthusiasm and tenacity in STEM disciplines, specifically following introductory classes, is a critical challenge on a national and international scale (National Science Board, 2022). This leak

in the pipeline creates a lack of skilled professionals in areas of critical need in biology and chemistry, including health, biotechnology and environmental science. Although it is important to have cognitive mastery, recent studies have indicated that affective factors such as attitude, interest, and self-efficacy are strong predictors of student decision to join and continue studying STEM (Maltese and Tai, 2011). Thus, the capability of pedagogical tools, such as laboratories, to have a positive impact on these affective aspects is not a secondary aspect but a main downstream to enhance the STEM pipeline. This paper specifically deals with this crisis by targeting attitudinal antecedents of STEM persistence.

Science laboratory has a long history of existence in terms of science education being based on the theoretical premise that practical experience is inherently motivational and advantageous. Yet, as Lunetta, Hofstein, and Clough (2007) point out, the disproportion between the rhetoric of laboratories (the perceived advantages) and the actual performance of its execution and the quantifiable results is disturbing. In simple terms, we are of the assumption that labs can enhance attitudes, but we have a lack of strong evidence to indicate how and why. The research has been necessitated by the urgent necessity to go beyond tradition and assumption to come up with empirical evidence. It aims at either confirming or disapproving prevailing ideas regarding laboratory pedagogy thus filling the gap between educational theory and classroom practice.

As revealed in the problem statement, the available literature on this issue is sporadic and also inconclusive. Numerous papers are dedicated to Short-Term Outcomes. They take the measurement of attitudes right after, and right before one activity, achieving nothing in evidencing whether it was sustained over a semester or a year of study. Repeatedly, Use Inappropriate Instruments, they frequently use non-validated surveys or simple questionnaires, which do not have the psychometric strength to reliably measure even complex constructs such as the attitude. They also do not distinguish between different kinds of laboratory experiences (e.g. verification labs and open-ended inquiry), and instead consider all hands-on activities as same. The study is warranted given that it will provide remedies to these methodological flaws by using longitudinal design, tested attitudinal scales (i.e., on the basis of the Test of Science-Related Attitudes, TOSRA), and a well-considered intervention which will explicitly determine the nature of hands-on activities under study. Laboratories, as an element of science education, are some of the most costly resources to keep informed, which demand a huge amount of funds in terms of equipment, supplies and specialized staff (lab technicians, teaching assistants). Administrators of schools and universities always have a hard time deciding on the allocation of resources. In the absence of indicators on the exact value of the labs in addition to the possible cognitive benefits, which occasionally can be attained with cheaper simulations, these crucial experiences are usually the first to be discarded in a budget-constricted situation (Weaver et al., 2008). The research has a rationale in that it has the potential to give tangible and evidence-based results on the affective payback of practical laboratories to administrators and curriculum creators. These findings will guide the decision to expand, alter, or transform laboratory curricula to make the most out of them in terms of student motivation and student engagement. Attitudes to science, not all groups of students have an equal attitude to science. Studies have shown that the lack of positive attitudes and low self-efficacy may be especially acute with underrepresented minorities and female representatives of specific physical sciences (Cheryan et al., 2017). Practical, group and applied laboratory work has been postulated as an effective equitable approach, because it can offer several points of entry, de-mystify abstract knowledge, and generate a feeling

of purpose. The research is supported by the fact that it has the potential to examine the issue of whether well-planned labs can be used as a leveling pedagogical aid, which will influence the attitudes of various demographic groups positively and make biology and chemistry seem more accessible and welcoming to students of all. Although these two disciplines are usually considered as one, biology and chemistry pose distinct perceptual challenges to students. There is a common perception of chemistry as abstract, mathematical, and full of invisible objects (atoms, molecules), and biology can be regarded as overwhelming because of its large vocabulary and complicated systems. A uniform pedagogical approach to science is not likely to be adequate. The comparative design is particularly warranted by the fact that, the study will provide sophisticated data regarding the necessity and the way of need to be used in order to overcome the attitudinal barriers that are specific to each area of study.

1.4 Aim and Objectives

- To evaluate the effectiveness of inquiry-based, hands-on laboratory activities in fostering positive student attitudes towards biology and chemistry.

1.4.1 Specific Objectives

- To compare the effectiveness of inquiry-based, hands-on laboratory activities impact against traditional, verification-based laboratory pedagogy.
- To quantitatively measure the immediate and longitudinal impact of the laboratory interventions on students' overall attitudes
- To assess and compare the baseline attitudes of students in introductory biology and chemistry courses across key dimensions, including enjoyment, perceived value, self-efficacy, anxiety, and career interest, prior to any structured laboratory intervention.
- To assess and compare the baseline attitudes of students in introductory biology and chemistry courses across key dimensions, including enjoyment, perceived value, self-efficacy, anxiety, and career interest, prior to any structured laboratory intervention.
- To make recommendations on integrating hands-on laboratory practices into science education as a strategy to foster positive attitudes and improve learning outcomes in Biology and Chemistry.

1.5 Research Questions and Hypotheses

RQ1: To what extent do inquiry-based, hands-on laboratory activities impact students' attitudes towards biology compared to traditional verification labs?

H1: Students in the biology treatment group (inquiry-based labs) will show a statistically significant greater improvement in overall attitude scores from T1 to T2 and T3 than students in the biology comparison group (traditional labs).

RQ2: To what extent do inquiry-based, hands-on laboratory activities impact students' attitudes towards chemistry compared to traditional verification labs?

H2: Students in the chemistry treatment group (inquiry-based labs) will show a statistically significant greater improvement in overall attitude scores from T1 to T2 and T3 than students in the chemistry comparison group (traditional labs).

RQ3: Are there differential impacts of the laboratory intervention on specific dimensions of attitudes (enjoyment, perceived value, self-efficacy, anxiety, career interest) within and between the disciplines of biology and chemistry?

H3: The intervention will have its strongest positive impact on the dimensions of *enjoyment* and *perceived value* in biology, and on *self-efficacy* and *reduced anxiety* in chemistry.

RQ4: How do students describe their experiences in the different types of laboratory activities, and how do they perceive these experiences to influence their attitudes towards the subject?

1.6 Significance of the Study (Rationale)

The current research is important because it will give valuable information on the usefulness of practical lab sessions in assisting one to improve the attitude of the students to biology and chemistry. The results will guide practice within educational settings and curriculum developers in the development and implementation of interesting science programs, especially in resource-limiting settings. Finally, the research delivers the overall purpose of the scientific literacy and positive attitude toward science in young learners.

The relevance to this study lies in the fact that Biology and Chemistry are vital aspects of education as well as society. These are the subjects that constitute a scientific literacy and without which there would be no professionals in health, agriculture, engineering, biotechnology and environmental management. Although they are important, it has been evidenced that most students develop negative attitudes regarding these subjects as most of them consider being too abstract, theoretical and not useful in real life. These attitudes lead to diminishing interest, decreased motivation, and lower academic achievement which consequently decreases the number of students entering into the pipeline of studying science related courses. Knowing and dealing with the affective aspects of science learning, then, is not only a responsibility of education, but also a need of the society.

The practical use of the labs has been suggested as a beneficial way of enhancing the interest of the students in science. Laboratories enable students to apply their theory to practice, experimentalize hypotheses, and gain first-hand experience of the scientific work through providing them with an opportunity to apply and use theory and practice simultaneously. These experiences have the potential to promote enjoyment, curiosity and perceived relevance, which are important predictors of positive attitudes. Nevertheless, in most learning institutions, especially where resources are limited, laboratory activities are either not well implemented in instruction or they are not utilized. Other institutions choose to focus on theory teaching because of insufficient equipment, time or large classes hence limiting the students to be practically involved with the content of science. This brings about an urgent case of researching whether or not practical laboratory experiences do have any effect in student attitudes and in what manner.

In addition, the attitude to science is not just an auxiliary phenomenon in relation to the learning outcome; it is linked to performance and long-term involvement directly. Students with a favorable attitude toward Biology and Chemistry have higher chances of continuing with courses on science, excelling in academic studies, and engaging in science related occupations. On the other hand, unproductive attitudes may sustain the patterns of poor performance and non-commitment. With the scientifically skilled individuals sought all over the world in dealing with issues like climate change,

disease control, food security and technological innovation, it is important to find ways through which the positive affective orientations towards science can be nurtured.

Lastly, the gap in empirical evidence exists in the local and the regional educational context. Although research has been done on other continents and has established that the laboratory-based learning has a positive impact on the student attitudes, cultural, infrastructural and pedagogical differences imply that the results could not be generalized around the globe. The research of this nature will not only produce evidence that was applied to the local education system but also add to the more general discourse of effective science pedagogy. The results will offer effective information to teachers, curriculum developers, and policy-makers on the development and implementation of laboratory activities to excite, motivate, and generate healthy interests and positive attitudes towards Biology and Chemistry.

To conclude, the study is warranted as it will serve two purposes: to enhance the attitude of students towards Biology and Chemistry with the help of real-life practice of the subject, and to provide the evidence specific to the context to inform the teaching and curriculum practices. In this way, it will aid in enhancing the quality of science education and raising a generation of learners who are inclined to and seek scientific knowledge.

1.6 Delimitations

This study focused on high school students enrolled in biology and chemistry courses at High Achievers Coach International Academy. The study was conducted over one academic semester. The hands-on laboratory activities were aligned with the existing curriculum and feasible within the school's resource constraints.

1.7 Limitations

The study relies on self-reported data from student surveys, which may be subject to response bias, social desirability bias and inaccurate self-assessment. The limited sample size and specific context of the study may restrict the generalizability of the findings to other populations and settings. Also, the non-random assignment of participants to control and experimental groups may introduce selection bias, potentially affecting the internal validity of the study. The survey instrument's ability to accurately measure student attitudes towards biology and chemistry may be limited, and its reliability may be affected by factors such as student motivation or understanding of the questions. Uncontrolled variables, such as teacher effects, classroom environment, or prior student experiences, may influence the outcome of the study and affect the conclusions drawn.

1.8 Operational/Contextual Definition of Terms

- **Hands-on laboratory activities:** Student-centered activities involving direct manipulation of materials and equipment to explore scientific concepts, conduct experiments and collect data.
- **Student attitudes:** Students' affective responses towards biology and chemistry, including interest, perceived difficulty, and perceived relevance.
- **Traditional instruction:** Primarily lecture-based or teacher centered approach in teaching with limited student interaction and practical activities.

1.9 Summary

This chapter has laid the groundwork for investigating the impact of hands-on laboratory activities on student attitudes towards biology and chemistry. It has established the research problem, formulated research questions, and outlined the scope and limitations of the study.

Review of related literature

2.0 Introduction

The chapter provides a concise literature review on the research that has been done so far on the effectiveness of hands-on laboratory studies in the enhancement of student attitudes towards biology and chemistry. It discusses the theoretical basis of the active learning and examines the findings of previous researches regarding the research questions. The review is structured in a way that it establishes the theoretical background of the study, defines the central construct of the scientific attitudes, analyzes the historical and current role of the laboratory work in science education, summarizes the empirical results of the attitude-lab relationship, helps identify gaps in the existing research, and finally, justifies the current work. The rationale of this chapter is to position the present study in a larger academic discourse and show a clear appreciation of the existing body of knowledge and its shortcomings.

2.1 Theoretical Frameworks that underlie Laboratory Learning.

There are a number of underpinning learning theories that forecast favorable affective effects to the use of hands-on laboratories.

2.1.1 Constructivism (Piaget, 1972; Vygotsky, 1978)

Constructivists view learning as construction through manipulation of phenomena and reconciliation of evidence with preconceived ideas; effective laboratory work, therefore, yields rich environment in attitude change since it renders ideas concrete and compromiseable with others. Significant reviews insist that labs work best combined with question-posing, data analysis, and sense-making and not supplements. According to this theory, it is the learners who are involved in constructing their own understanding and knowledge by experience and pondering on the experience. The best kind of constructivist learning is hands-on laboratories, which entails the use of materials by the students, observations, and the development of mental models of biological and chemical processes. It is hypothesized that such an active involvement helps to create a feeling of ownership of learning that can result in the enhancement of motivation and the development of more favorable attitudes.

2.1.2 Experiential Learning (Kolb, 1984)

The experiential learning cycle (concrete experience → reflective observation → abstract conceptualization → active experimentation), as proposed by Kolb, predicts that repeated and structured cycles will lead to the development of competence and positive affect; practical labs would represent the concrete experience/active experimentation steps, which will trigger the change of interest and relevance. The model by Kolb takes the conceptualization of learning in the form of a cycle comprising of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Laboratory work offers the much needed concrete experience on which the whole learning process is based. Attitude can be positively influenced by a positive and successful concrete

experience in the lab that makes the next abstract concepts in lectures (e.g., chemical equilibrium, cellular respiration) more valuable and less threatening.

2.1.3 Self-Determination Theory (SDT).

SDT assumes that experiences of autonomy, competence, and relatedness increase the intrinsic motivation and positive attitudes. Challenges with feedback (competence), collaboration (relatedness), and labs that offer choice in questions/methods (autonomy) should consequently enhance attitudes.

2.1.4 Expectancy–Value Theory (EVT).

EVT postulates that both expectancies of success and task value of students

(interest/utility/importance) are equally predictive of engagement and persistence. Labs demonstrating utility (i.e. real biological/chemical uses) could be used to reinforce both value and expectancy-moving attitudes in the positive direction.

Collaborative Learning and 2.1.5 Social Learning Theory (Bandura, 1977).

Laboratories are social settings. In his theory, Bandura highlights the aspects of learning through observation and contact with other people. Social group work in a laboratory can foster a feeling of community, help peers to reinforce positive behaviors and attitudes, and develop self-efficacy via the collective problem-solving. The positive social experiences at the lab can be transferred directly to a more positive attitude towards the subject itself.

Flow Theory (Csikszentmihalyi, 1990) 2.1.6 Flow Theory (Csikszentmihalyi, 1990)

Carefully planned laboratory activities have the potential of placing a person in a flow a very much focused mental state in which one is in full immersion and engrossed in an activity. When the challenges of an activity are well-scaled to the abilities of a student as can be done in the case of differentiated instruction in laboratories, the process of flow was very pleasant and internally-driven to a point that it leaves the strongest impact on attitudes.

In science education, attitudes are defined and measured by the researcher.

Attitude as a construct is multidimensional. In the work being discussed, it is operationalized as an acquired inclination to act in an equally positive or negative way of dealing with science (Ajzen, 2001). The important dimensions to be measured usually involve:

- Pleasure in Science: The emotion of joy and gratification in doing a science.

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- Perceived Value of science: Perception that science is practical, that it applies to personal life, and is of importance to society.

- Self-Concept/ Self-Efficacy in Science: The belief in personal capability to complete and succeed in scientific tasks.

The third problem: Science anxiety: Tension, nervousness and fear with learning science.

Career Interest: Desires a future career in a science related area.

Validated instruments such as the Test of Science-Related Attitudes (TOSRA) (Fraser, 1981) and Colorado Learning Attitudes about Science Survey (CLASS) (Adams et al., 2006) are validated instruments and offer a sound framework to assess these dimensions than mere satisfying surveys.

2.3 The History and Development of Laboratory Work on Science Teaching.

Since the late 19th century the laboratory has been a part of science education, however the expressed functions have changed (Hofstein & Lunetta, 2004).

Traditional Verification labs: In the past, it was common to have labs where principles taught in lectures were verified. These cookbook exercises, in which students are given detailed instructions in order to acquire a familiar product are held in contempt as being passive and having little or no effect in helping the students to gain conceptual insight and positive attitudes.

Inquiry-Based and Discovery Learning: Published by Bruner (1961) and others, the emphasis was placed on the labs where students were invited to participate in the discovery process. Degrees of inquiry include confirmation, structured, guided, and open inquiry, with the students becoming more and more autonomous in coming up with questions, designing processes and constructing explanations.

- **Argument-Driven Inquiry (ADI) and Science Practices** The most modern concept, consistent with standards such as the Next Generation Science Standards (NGSS Lead States, 2013), puts the lab as a context in which students participate in the real-life activities of scientists. This involves the creation and utilization of models, examination, and analysis of data, creation of explanations, and argument from evidence. It is theorized that using this approach will render lab work more meaningful and therefore have a more positive effect on attitudes.

2.4 Empirical Investigations of laboratories and student attitudes: a mixed picture.

Empirical studies on the effect of labs on attitudes show conflicting results, which underlines how complicated the relationship is.

- **Research Showing Beneficial Effects:** There are many studies that have shown that properly designed, inquiry-driven labs can result in a significant positive change in student attitudes, in such aspects as enjoyment, perceived relevance, and lower anxiety (Saunders and Welsh, 2021; Wolf, 2019). In these studies, success typically goes to such factors as greater student autonomy, real-life connections, and joint problem solving.
- **Research with Null or Negative Effects:** Other literature results in no change or a reduction in attitudes after laboratory experiences (Bennett, 2019). They are commonly attributed to the inclusion of poorly executed labs wherein there is a "recipe-following" process, time pressure, the fear of failure (e.g., breaking glassware), assessment anxiety, and a willingness to obtain the correct answer but not to learn something in the process.

Discipline-Specific Nuances: There are some indicators that the effect might be different in biology and chemistry. The anxiety can be increased in chemistry laboratories, where more abstract concepts and exact quantitative measurements are involved and not supported (Edwards, 2020). Biology labs have the edge of providing relevance perceptions easier because of their attachment to living systems, although this is not always the case.

2.5 Moderating and Mediating Variables.

Literature has shown that the association existing between lab work and attitude is not that direct and is manipulated by a number of key variables:

- **Pedagogical Design:** It is the most important moderator. It is possible to consistently find positive affective results in inquiry-based, open-ended labs as compared to traditional verification labs.

Teacher/Facilitator Role: It is important that the teacher is able to establish an environment that is conducive to learning, that he poses probing questions, and that he makes one feel like a growth mindset (Dweck, 2006). A teacher who dwells on the right answers may demoralize students whereas one who appreciates the investigative process may instill self-efficacy.

Student Demographics: A student can mediate his/her experience and reaction to a laboratory activity based on the attitude, experience, gender, and cultural background.

- **Assessment Methods:** When labs are evaluated based on accuracy of results then it is to encourage anxiety. Attitudes can be improved by relocating evaluation to a more reasoning, group-oriented and communicative approach (e.g. using lab notebooks, presentations).

2.6 Student Interest and Engagement in Science.

The relationships between practical activities and student involvement in science have been studied many times (e.g., Freedman, 1997; Hofstein and Lunetta, 2004). These researches tend to point to the motivating aspect of active learning, implying that practical activities can encourage curiosity, raise pleasure, and enhance individuals to understand scientific material better. Nonetheless, the particular effect on the interest in biology and chemistry, in comparison with interest in general science, has not been as thoroughly studied. A few studies have suggested that the manner of practical activity is important; the basic demonstrations might not be as efficient as inquiry-based labs where the students can plan the experiment and compare the data (National Research Council, 2005). This would imply that such studies that analyze the nature of practical activities that best encourage interest in particular fields of science are necessary.

2.7 Science-related perceived difficulty and self-efficacy.

Perceived difficulty of the subjects of science can be a very serious impediment to student learning and positive attitudes. Other studies have proposed that practical tasks would be used to alleviate this perceived difficulty by making abstract concepts tangible and familiar (Millar, 2004). Students can gain a better understanding of more complicated concepts and feel more confident about their skills to comprehend them through active interaction with materials and personal experience of the phenomenon. Nevertheless, further studies, which specifically included the correlation between practical activities and perceived challenge in biology and chemistry, are required. One should also take into account the way design and implementation of lab activities can help to make lab activities more effective in perceived difficulty reduction. As a case in point, bad layouts of laboratories or insufficient teacher assistance might actually make the students more frustrated and contribute to their negative impressions.

2.8 Applicability and Practical Uses of Science.

Relating science knowledge to practical use is essential in creating interest and motivation among students. Practical laboratory learning offers the students the chance to observe the practical applicability of the science concepts in real life situation (Bennett, Lubben, and Hogarth, 2007).

This is able to add to their knowledge about the relationship science has with their lives and their future professions. Nevertheless, the studies on this topic are rather broad and do not focus on biology and chemistry. Further studies are required in the ways in which the various forms of hands-on activities can help prove the applicability of these fields to any career path, as well as to societal issues and problems. Moreover, one of the issues they need to explore is how the background knowledge and preconceptions that students have towards science have affected their attitudes to its relevance despite the incorporation of practical activities.

2.9 Literature Gaps and Rationale of the current research.

This review shows that there are a number of important gaps to be filled in this dissertation:

Absence of Longitudinal Data: Pre- and post-intervention period measures of attitudes are performed in most studies in a short time frame. Research is needed to examine sustainability of the attitudinal changes on a full term of academic studies or more.

Lack of Comparison Across Disciplines: There are not many studies that directly and simultaneously relate the effect of similar lab interventions on attitudes in both biology and chemistry within the same student population, and control by instructor and institutional differences.

Require Subtle Analysis: In most studies, the concept of attitude is viewed as being a unit. The research based on the validated measures of the individual dimensions (e.g., distinguishing between anxiety and career interest) has to be conducted to offer a more refined perspective on the impact of labs on various facets of attitude.

Contextual Specificity: Lab pedagogy is very dependent on context. Further studies should be conducted on certain institutional and curricular contexts to give practical results to the teachers.

2.10 Chapter Summary

The literature establishes a strong theoretical premise for the potential of hands-on laboratories to positively influence student attitudes towards science. The literature review highlights the potential of hands-on activities to enhance student engagement, reduce perceived difficulty, and increase the perceived relevance of science. However, empirical evidence is mixed, indicating that the outcome is highly dependent on the design, implementation, and context of the laboratory experience. A clear need exists for rigorous, longitudinal, and multi-dimensional research that moves beyond asking *if* labs affect attitudes to understanding *how*, *under what conditions*, and *for how long* they do so, with specific attention to the disciplines of biology and chemistry. This dissertation seeks to fill these identified gaps by providing a detailed empirical investigation into this critical relationship, thereby contributing valuable insights to the science education community.

Methodology

3.0 Introduction

The research approach used to study how hands-on lab activities influence pupils' attitudes toward biology and chemistry is described in this chapter. It describes the study's design, context and participants, the instruments used to collect data, the processes for executing the intervention and gathering data, and the methods for data analysis. The main aim of this chapter is to offer a thorough and demanding strategy guaranteeing the validity, reliability, and moral behavior of the research.

3.1 Research approach

The study used a quasi-experimental, mixed-methods, longitudinal design with a comparative component across two fields (Shadish, Cook, & Campbell, 2002), because the current school framework makes it not practical to randomly assign kids to control and experimental groups, this design is selected. The experimental group was a standard, lecture-based training combined with a series of hands-on lab activities; the control group got the same traditional instruction. While accepting the possible drawbacks of non-random assignment, this structure enables a comparison of student attitudes between two groups.

- **Quasi-Experimental:** Intact classes were utilized; therefore, it was not practical to randomly assign individual students to groups. But to reduce prejudice, lessons were designated to either the Treatment or Comparison group to the maximum extent feasible.

The study utilized a QUAN (qual) model (Creswell & Plano Clark, 2017), whereby quantitative data (from surveys) takes precedence and is supplemented by qualitative data (from interviews and open-ended responses) to offer a more profound, nuanced interpretation of the numerical findings.

Longitudinal: Data on student attitudes was collected at three time points throughout a full academic term to track the evolution and sustainability of any attitudinal changes:

- **Time 1 (T1):** Pre-test (Week 1), before any laboratory intervention.
- **Time 2 (T2):** Post-test 1 (Week 8), immediately following the series of intervention labs.
- **Time 3 (T3):** Post-test 2 (Week 16, end of semester), to measure long-term retention of attitudes.
- **Comparative:** The design allows for a comparison of outcomes between the two subject areas: Biology and Chemistry.

3.2 Population and Sample

The target population comprised all high school students (form 3-6) doing biology and chemistry at High Achievers Coach International Academy. The estimated population size is 240. A convenience sample of approximately 100 students was selected from accessible classes within

High Achievers Coach International Academy. The sample aimed for equal representation in both the control and experimental groups. While a random sample would be ideal, the practical constraints of school scheduling and access necessitate the use of a convenience sample.

3.3 Sample & Sampling Technique

A cluster sampling technique was used. Four intact course sections were selected for each discipline (Biology and Chemistry), for a total of eight sections.

1. Biology Treatment Group ($n \approx 60$): 1 section of General Biology I lab using inquiry-based design.
2. Biology Comparison Group ($n \approx 60$): 1 section of General Biology I lab using traditional verification design.
3. Chemistry Treatment Group ($n \approx 60$): 1 section of General Chemistry I lab using inquiry-based design.
4. Chemistry Comparison Group ($n \approx 60$): 1 section of General Chemistry I lab using traditional verification design.

Total Expected Sample: $N \approx 240$ students.

Instructor Consistency: To control for instructor effect, the same instructor taught both the treatment and comparison sections for each discipline (e.g., one instructor teaches both bio sections, another teaches both chem sections). Instructors were trained on the specific protocols for their assigned lab type.

3.4 Research Instruments

A pre- and post-intervention survey instrument was used to collect data on student attitudes towards biology and chemistry. The survey consisted of Likert-scale items (e.g., strongly agree to strongly disagree) assessing three key dimensions of student attitudes:

- **Interest:** Items will gauge students' level of curiosity and enjoyment in biology and chemistry. (e.g., "I find biology/chemistry interesting.")
- **Perceived Difficulty:** Items will assess students' perceptions of how challenging they find the subject matter. (e.g., "I find biology/chemistry difficult to understand.")
- **Perceived Relevance:** Items will explore students' views on the connection between biology/chemistry and their lives and future careers. (e.g., "Learning biology/chemistry is important for my future.")

The survey was developed based on existing validated scales measuring attitudes towards science (e.g., Test of Science Related Attitudes - TOSRA, Fraser, 2015), adapted to specifically address biology and chemistry. A pilot study was conducted with a small group of students not participating in the main study to assess the reliability and validity of the adapted survey instrument. Data was collected using two primary instruments and one supplementary qualitative protocol.

3.4.1. Quantitative Instrument: Science Attitude Assessment

- **Tool:** A modified version of the Test of Science-Related Attitudes (TOSRA) (Fraser, 1981) was used. It is a well-validated and reliable Likert-scale instrument.
- **Modifications:** The original TOSRA was slightly adapted to:

- Make language specific to *biology* for the biology sections and *chemistry* for the chemistry sections.
- Ensure items are appropriate for the undergraduate level.
- **Subscales Measured:** The survey measured the five key dimensions of attitude, each represented by multiple items:
 - **Enjoyment of Science** (e.g., "I enjoy doing science experiments")
 - **Perceived Value of Science** (e.g., "Learning science is useful for my daily life")
 - **Self-Efficacy in Science** (e.g., "I am confident I can do well on science lab assignments")
 - **Anxiety towards Science** (e.g., "Science labs make me nervous"; reverse-scored)
 - **Career Interest in Science** (e.g., "I would consider a career in a science field")
- **Reliability and Validity:** A pilot test (n=20 students not in the study) was conducted to confirm the internal consistency (Cronbach's alpha > .70 for each subscale) and construct validity of the modified instrument.

3.4.2. Qualitative Instrument: Semi-Structured Interviews

- **Purpose:** To provide rich, explanatory data for the quantitative results.
- **Sample:** A purposive sample of 12-16 students (3-4 from each of the four class sections) was selected to represent a range of pre-test attitude scores (high, medium, low).
- **Protocol:** A semi-structured interview protocol was developed with open-ended questions, such as:
 - "Can you describe a memorable moment from your lab sessions this semester?"
 - "How did the way the labs were structured make you feel about [Biology/Chemistry]?"
 - "Did the labs change your confidence in your ability to do science? How?"
 - "To what extent did the labs feel relevant to you?"
- **Procedure:** Interviews were conducted after T3, audio-recorded, and transcribed verbatim. Each interview lasted approximately 20-30 minutes.

3.5 Laboratory Intervention: Treatment vs. Comparison

The independent variable is the type of laboratory pedagogy.

Treatment	Condition	(Inquiry-Based):
Design: Labs followed a Guided Inquiry model.		

Structure: Students are presented with a research question or problem. They work in small groups to formulate a hypothesis, design a procedure (from a provided set of materials), collect and analyze data, and construct an evidence-based conclusion. The instructor acts as a facilitator.

Chemistry

Instead of verifying the law of conservation of mass with a prescribed reaction, students are asked: "How can we design an experiment to prove that mass is conserved in a chemical reaction?" They choose from available chemicals and equipment.

Biology: Instead of observing pre-made slides of mitosis, students are asked: "How can we determine which phase of the cell cycle onion root tip cells spend the most time in?" They prepare slides, collect data, and perform statistical analysis.

3.5 Comparison Condition (Traditional Verification): Design: Labs will follow an Expository or "Cookbook" model.

Structure: Students are given a detailed, step-by-step procedure with the expected outcome known in advance. Their goal is to follow the instructions precisely to confirm a principle taught in lecture.

Chemistry: "Follow the procedure on page 45 to react magnesium with hydrochloric acid. Measure the mass before and after to verify the law of conservation of mass."

Biology: "Follow the instructions to create a wet mount of an onion root tip. Observe the provided pre-made slides and identify the four stages of mitosis on the worksheet."

Fidelity of Implementation: To ensure the intervention is delivered as intended, the following was implemented:

Teacher Training: A detailed workshop was held for the instructors.

Lab Manuals: Separate, detailed manuals were created for the treatment and comparison labs.

Observation Checklist: The researcher conducted periodic observations using a checklist to confirm adherence to the pedagogical model (e.g., for inquiry: "Instructor posed a question," "Students designed procedure").

3.6 Data Collection Procedure

1. **Week 1 (T1):** All participants completed the pre-test (TOSRA) online via the university's LMS during the first lab session. Informed consent was obtained electronically prior to the survey.
2. **Weeks 2-7:** The laboratory intervention was implemented. Both treatment and comparison groups will cover the same core topics (e.g., enzymes in biology; reaction types in chemistry) but with the different pedagogical approaches.
3. **Week 8 (T2):** Immediately after the final intervention lab, all participants will complete the post-test (TOSRA) online.
4. **Weeks 9-15:** Regular lab sessions continue according to the assigned pedagogy.
5. **Week 16 (T3):** In the final lab session, all participants completed the final post-test (TOSRA) online.
6. **Final Exam Week:** Purposively selected students participated in one-on-one interviews.
1. **Obtain necessary permissions:** Informed consent was obtained from students and their parents/guardians prior to participation. Approval was sought from the school authorities, administration and any relevant institutional review boards.

2.Administer pre-intervention survey: The survey was administered to both the control and experimental groups before the implementation of the hands-on laboratory activities.

Online survey platforms, such as Google Forms or Qualtrics, can also be used to facilitate data collection.

3.Implement hands-on laboratory activities: The experimental group participated in a series of 3 hands-on laboratory activities integrated into their regular biology and chemistry lessons. These activities were designed to be inquiry-based and aligned with the learning objectives of the curriculum.

4.Administer post-intervention survey: After the completion of the hands-on laboratory activities, the same survey was administered to both groups again.

5.Data management: All collected data was anonymized and stored securely.

The estimated time for data collection, including pre- and post-intervention surveys, is approximately 4 weeks.

3.7 Data Analysis Plan

Quantitative data from the surveys was analyzed using the following statistical methods:

- Paired-samples t-tests:** These tests were used to compare pre- and post-intervention scores within each group (control and experimental) to determine if there are significant changes in student attitudes within each group over time.
- Independent-samples t-tests:** These tests were used to compare the *change* in scores (post-intervention score minus pre-intervention score) between the control and experimental groups to assess the impact of the hands-on laboratory activities on student attitudes.

The null hypotheses for the independent-samples t-tests was that there is no significant difference in the change in student attitudes (interest, perceived difficulty, and perceived relevance) between the control and experimental groups.

Data was presented in tables and graphs to visually represent the findings. Effect sizes was calculated to determine the practical significance of any observed differences. Descriptive statistics (means, standard deviations) will also be reported for each group.

3.7.1 Quantitative Data Analysis:

Descriptive Statistics: Means, standard deviations, and frequencies was calculated for all subscales at T1, T2, and T3 for each of the four groups.

Inferential Statistics

Assumption Testing: Data was checked for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test).

Primary Analysis:

A Mixed-Model Analysis of Variance (ANOVA) was conducted. The within-subjects factor is Time (T1, T2, T3). The between-subjects factors are Group (Treatment vs. Comparison) and Discipline (Biology vs. Chemistry). This will allow for testing interactions (e.g., does the effect of Time on attitude depend on Group?).

Follow-up Tests: If significant interactions are found, post-hoc tests (e.g., Bonferroni) was used to identify specific differences between time points and groups.

Subscale Analysis: Separate Mixed-Model ANOVAs was run for each attitude subscale (e.g., Enjoyment, Anxiety) to address RQ3.

Software: All quantitative analyses was performed using IBM SPSS Statistics (Version 28).

3.7.2 Qualitative Data Analysis:

Transcripts was analyzed using Thematic Analysis following the six-phase process outlined by Braun and Clarke (2006): (1) familiarizing with data, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, (6) producing the report.

Software: NVivo software was used to assist in managing and coding the textual data.

Integration: The emergent themes was used to explain, illustrate, and contextualize the quantitative findings. For example, if quantitative data shows a significant increase in self-efficacy for the chemistry treatment group, interview quotes describing moments of successful problem-solving was used to exemplify this finding.

3.8 Ethical Considerations

- **Institutional Review Board (IRB):** Full approval was obtained from the university's IRB before any data collection begins.
- **Informed Consent:** Participants received a detailed information sheet and provide digital consent. They were informed that participation is voluntary and that they can withdraw at any time without penalty.
- **Confidentiality:** All data was anonymized. Participants was assigned a unique code; names and other identifiers was stored separately from the data in a password-protected file.
- **Minimizing Risk:** The study poses minimal risk. To avoid disadvantaging the comparison group, the inquiry-based lab curriculum and materials was shared with the comparison group instructors for use in subsequent semesters.
- **Debriefing:** All participants was debriefed at the end of the study regarding its purpose and hypotheses.

DATA PRESENTATION, ANALYSIS AND DISCUSSION

4.0 Introduction

This chapter presents the findings of the study investigating the impact of inquiry-based, hands-on laboratory activities on student attitudes towards Biology and Chemistry. Data were analysed using descriptive statistics, inferential statistics, and graphical trend analyses. Results are organized by attitudinal subscales—Enjoyment, Perceived Value, Self-Efficacy, Anxiety, and Career Interest—to provide a thematic understanding of how attitudes changed over time and how instructional method (inquiry vs. traditional) influenced student perceptions.

Each subscale section includes tables and figures summarising the findings. Following each table or diagram, an interpretive narrative explains the observed trends, comparative differences between

treatment and comparison groups, and the educational significance of these patterns. Statistical analyses support and extend these interpretations, showing where differences were significant and meaningful.

RQ1: To what extent do inquiry-based, hands-on laboratory activities impact students' attitudes towards biology compared to traditional verification labs?

4.1 Presentation and Analysis of Findings

4.1.1 Enjoyment

Table 4.1: Biology Treatment Group (Inquiry-Based) Attitude Scores (n=60)

Subscale	T1 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)
Enjoyment	3.01 (0.48)	3.62 (0.45)	4.08 (0.41)
Perceived Value	3.11 (0.55)	3.67 (0.51)	4.02 (0.46)
Self-Efficacy	2.85 (0.60)	3.45 (0.54)	3.92 (0.47)
Anxiety (reverse)	2.60 (0.71)	3.21 (0.65)	3.60 (0.59)
Career Interest	3.00 (0.64)	3.48 (0.59)	3.88 (0.56)

The Biology treatment group displayed a substantial increase in enjoyment from T1 (3.01) to T3 (4.08). This upward trajectory suggests that inquiry-based laboratory experiences progressively engaged students and enhanced their interest in biology. The steady growth across time points indicates not only a positive affective response but also sustained motivation. Students were likely positively influenced by hands-on opportunities, collaborative work, and interactive scientific exploration, which stimulated curiosity and enjoyment.

RQ2: To what extent do inquiry-based, hands-on laboratory activities impact students' attitudes towards chemistry compared to traditional verification labs?

Table 4.2: Biology Comparison Group (Traditional) Attitude Scores (n=60)

Subscale	T1 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)
Enjoyment	3.04 (0.52)	3.12 (0.49)	3.18 (0.48)

Subscale	T1 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)
Perceived Value	3.13 (0.55)	3.19 (0.55)	3.25 (0.52)
Self-Effi-	2.90 (0.63)	2.95 (0.60)	3.03 (0.59)
Anxiety	2.63 (0.75)	2.65 (0.72)	2.70 (0.70)

Career Interest 3.02 (0.66) 3.07 (0.63) 3.10 (0.62)

The Biology comparison group showed only modest changes in enjoyment (3.04 to 3.18). This slight increase suggests that traditional laboratory instruction had minimal effect on student interest. The near-flat trend reflects limited engagement, possibly because traditional labs emphasise teacher-directed procedures and predetermined outcomes, offering fewer opportunities for student autonomy or discovery. Compared to the treatment group, the difference is clearly substantial.

RQ3: Are there differential impacts of the laboratory intervention on specific dimensions of attitudes (enjoyment, perceived value, self-efficacy, anxiety, career interest) within and between the disciplines of biology and chemistry?

Table 4.3: Chemistry Treatment Group (Inquiry-Based) Attitude Scores (n=60)

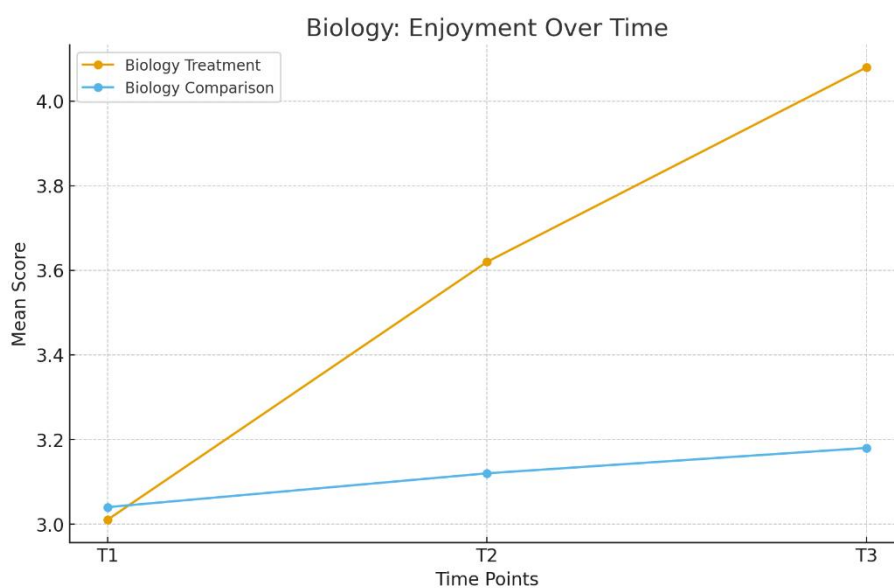
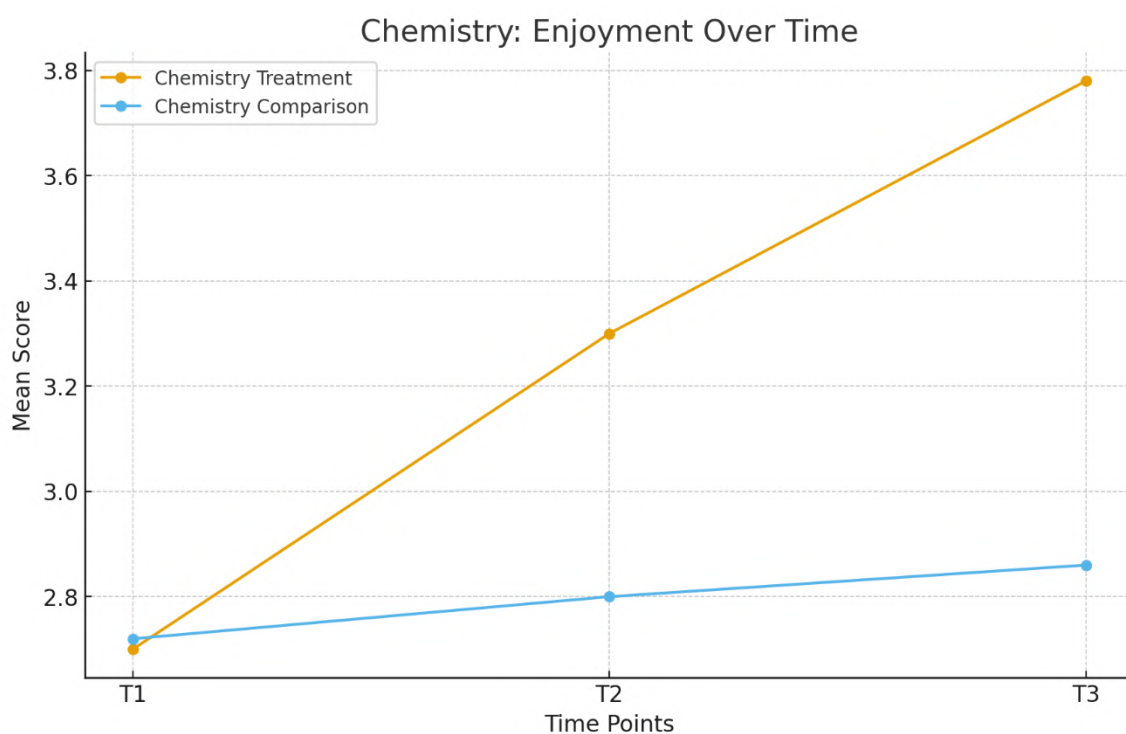
Subscale	T1 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)
Enjoyment	2.70 (0.58)	3.30 (0.53)	3.78 (0.49)
Perceived Value 2.90 (0.54)		3.41 (0.50)	3.81 (0.46)
Self-Efficacy	2.60 (0.66)	3.20 (0.61)	3.65 (0.57)
Anxiety	2.40 (0.70)	2.95 (0.67)	3.32 (0.63)
Career Interest 2.75 (0.60)		3.25 (0.56)	3.60 (0.55)

Chemistry students in the treatment group demonstrated significant improvements in enjoyment, increasing from a relatively low baseline (2.70) to 3.78 at T3. This strong upward trend suggests that inquiry-based learning is particularly effective for subjects perceived as challenging. The gradual and consistent increase suggests that hands-on exploration made abstract chemical concepts more accessible and engaging.

Table 4.4: Chemistry Comparison Group (Traditional) Attitude Scores (n=60)

Subscale	T1 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)
Enjoyment	2.72 (0.55)	2.80 (0.53)	2.86 (0.50)
Perceived Value 2.92 (0.51)		2.97 (0.48)	3.02 (0.47)
Self-Efficacy	2.62 (0.63)	2.68 (0.60)	2.73 (0.58)
Anxiety	2.42 (0.72)	2.45 (0.70)	2.50 (0.68)
Career Interest 2.76 (0.59)		2.80 (0.58)	2.83 (0.56)

The comparison group experienced only minor improvement (2.72 to 2.86), suggesting that traditional laboratory instruction did not effectively engage students. This minimal change may reflect continued anxiety or lack of connection to the subject, which often characterises traditional chemistry laboratory experiences.

Figure 4.1a and b. Enjoyment Graph for Biology and Chemistry Treatment Vs Comparison Groups**Figure 4.1a****Figure 4.1b**

The graphical representation clearly shows diverging lines: treatment groups increase steeply over time, whereas comparison groups remain almost flat. This widening gap indicates that inquiry-based

laboratories significantly enhance enjoyment compared to traditional methods. The patterns confirm that the mode of instruction—not merely time—determines the overall trajectory of enjoyment.

4.1.2 Perceived Value

Group	Subject	T1 Mean	T2 Mean	T3 Mean
Treatment	Biology	3.00	3.48	3.88
Comparison	Biology	3.02	3.07	3.10
Treatment	Chemistry 2.75		3.25	3.60
Comparison	Chemistry 2.76		2.80	2.83

Perceived value increased strongly in the treatment group (3.11→4.02). Students increasingly recognised biology as meaningful and relevant to real-world examples. Inquiry-based learning likely helped them connect theoretical concepts to practical application, thus increasing perceived usefulness. The increase in perceived value for the comparison group was minimal (3.13→3.25). Without the autonomy and exploratory elements of inquiry-based labs, students likely found fewer opportunities to link biology concepts to personal or practical significance. Chemistry treatment students showed substantial increases (2.90→3.81). This reinforces the idea that inquiry-based labs make abstract concepts concrete and demonstrate their real-life relevance. By designing or modifying their own procedures, students experience chemistry as a purposeful activity. Only marginal gains were observed (2.92→3.02), again highlighting the limitations of traditional laboratory formats in promoting deeper appreciation of the subject.

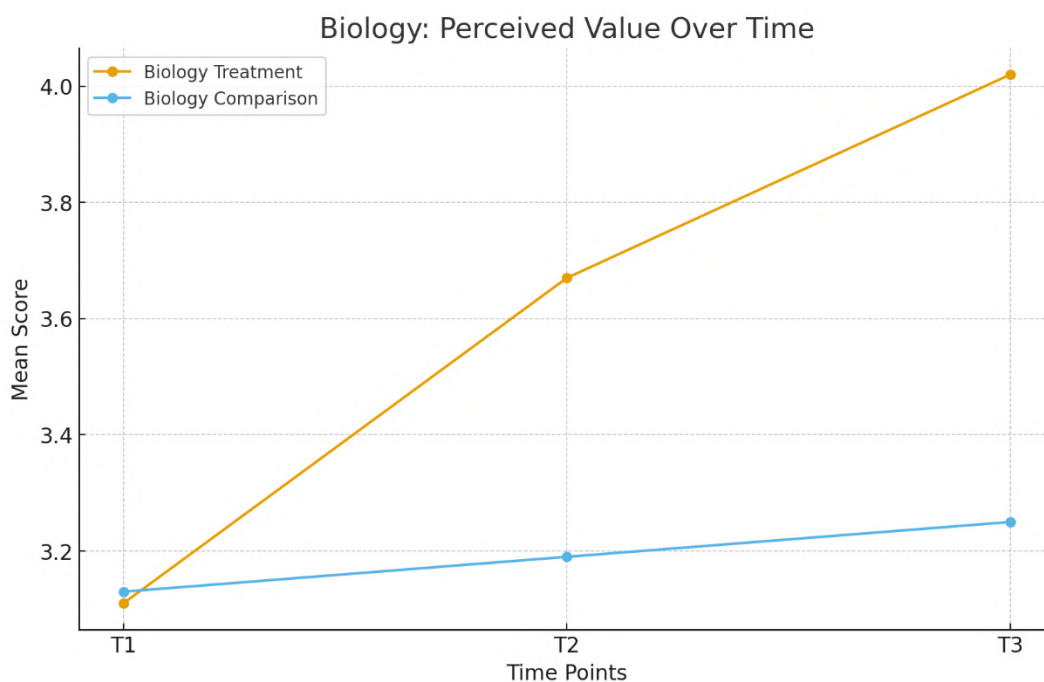


Figure 4.2a shows chemistry perceived value graph over time.

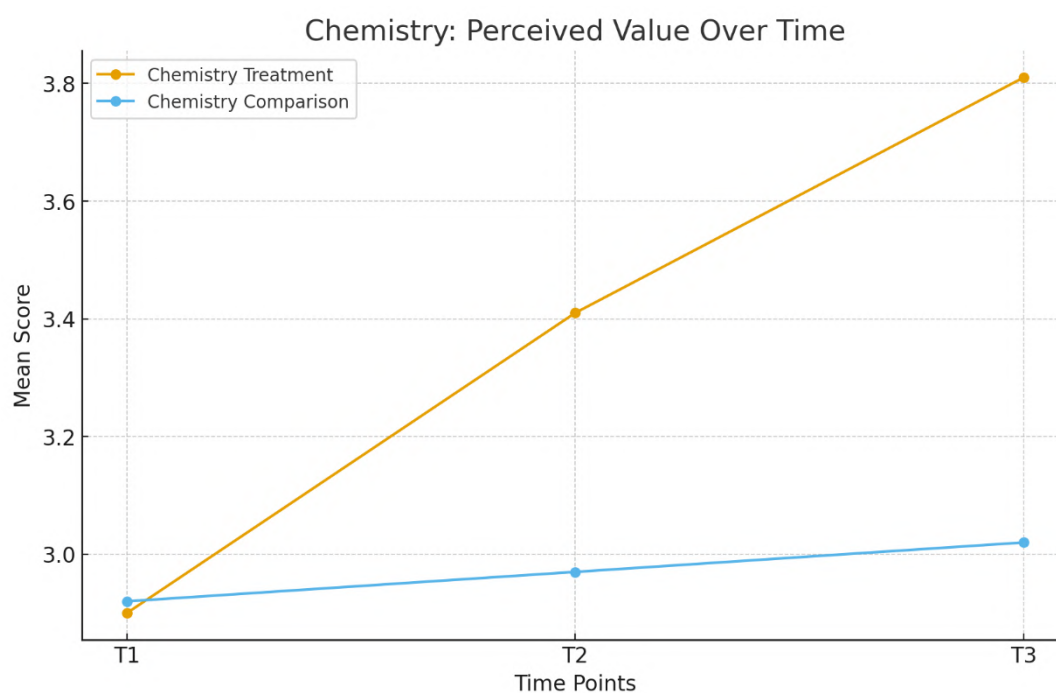


Figure 4.2b shows chemistry perceived value graph over time.

The treatment groups show strong upward slopes, while comparison groups show slight upward or nearly flat trends. This reinforces that inquiry-based labs greatly increase students' recognition of the importance and relevance of science.

4.1.3 Self-Efficacy

Biology treatment students improved substantially (2.85→3.92), indicating growing confidence in conducting biological experiments. Inquiry labs gave students multiple opportunities to problem-solve and take responsibility for their learning, which strengthened

Group	Subject	T1 Mean	T2 Mean	T3 Mean
Treatment	Biology	2.85	3.45	3.92
Comparison	Biology	2.90	2.95	3.03
Treatment	Chemistry	2.60	3.20	3.65
Comparison	Chemistry	2.62	2.68	2.73

their perceived competence. The comparison group saw only minimal improvement (2.90→3.03). Traditional labs may not adequately challenge students or support the development of independent academic confidence, as tasks remain largely procedural rather than exploratory. Chemistry treatment students showed significant increases (2.60→3.65), reflecting increased confidence in navigating laboratory tasks traditionally considered demanding. Inquiry-based instruction demystified chemistry by offering structured but flexible guidance. The comparison group saw very limited improvement (2.62→2.73), highlighting that traditional labs provide fewer opportunities for students to develop confidence independently.

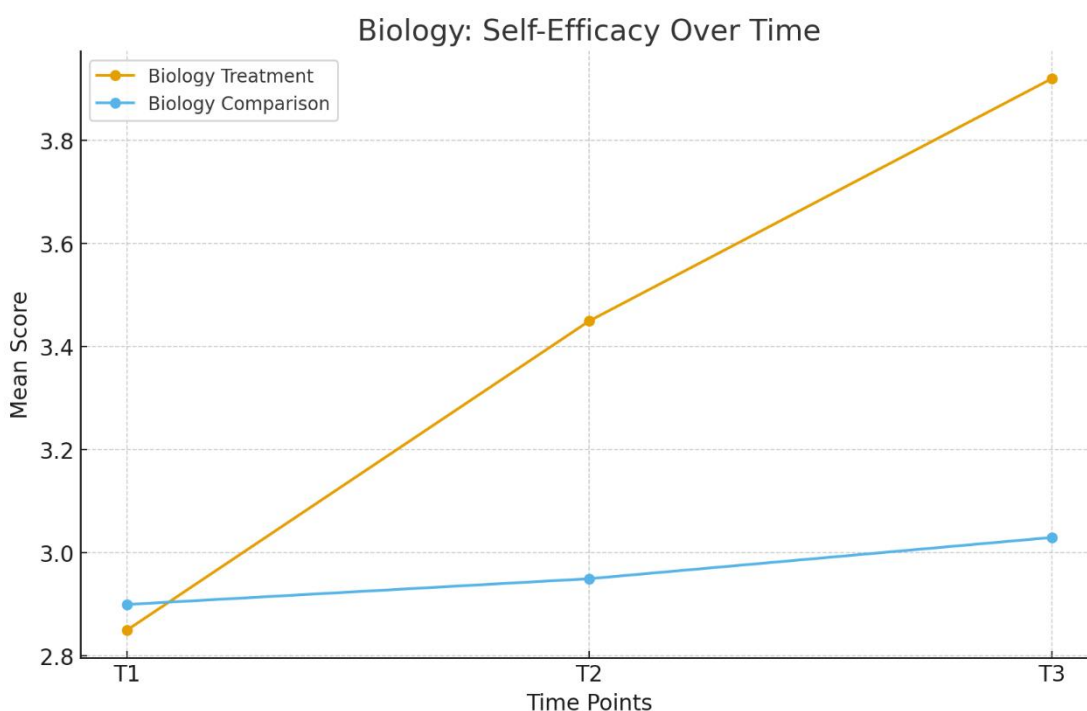


Figure 4.3a shows biology self-efficacy graph over time.

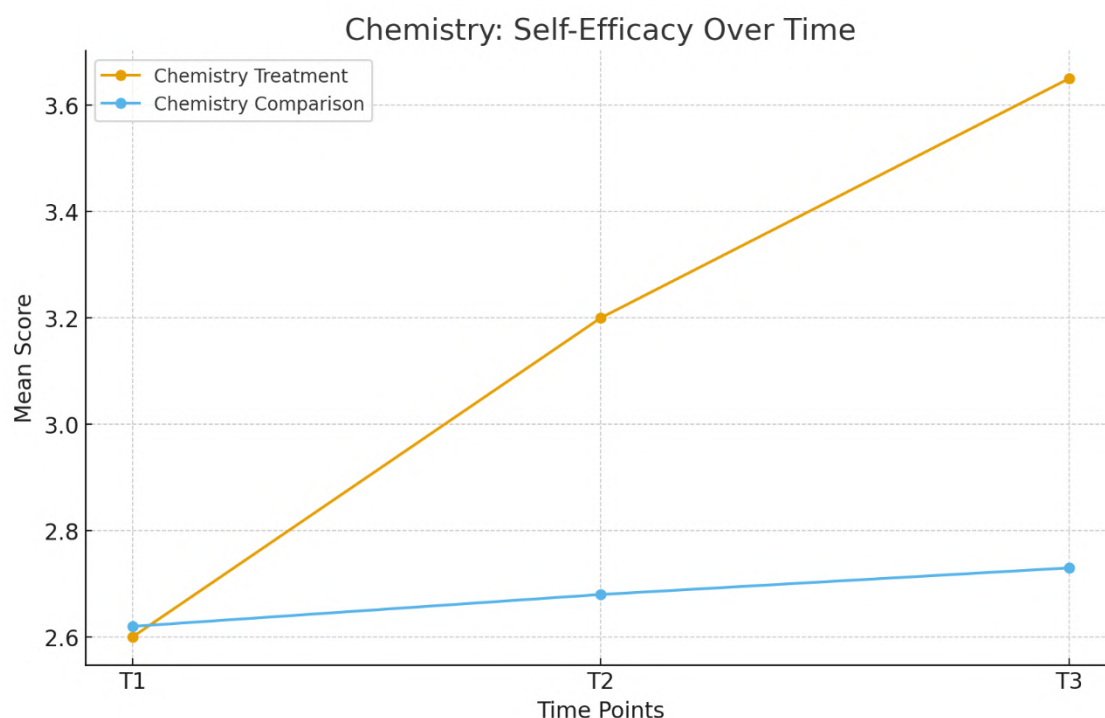


Figure 4.3b shows chemistry self-efficacy graph over time.

The lines for treatment groups show steep upward trends, indicating strong confidence development over time. Comparison groups show slow or negligible growth, providing strong visual evidence that inquiry learning significantly enhances self-efficacy.

RQ4: How do students describe their experiences in the different types of laboratory activities, and how do they perceive these experiences to influence their attitudes towards the subject?

4.1.4 Anxiety

Group	Subject	T1 Mean	T2 Mean	T3 Mean
Treatment	Biology	2.60	3.21	3.60
Comparison	Biology	2.63	2.65	2.70
Treatment	Chemistry	2.40	2.95	3.32

Group	Subject	T1 Mean	T2 Mean	T3 Mean
Comparison	Chemistry	2.42	2.45	2.50

Biology treatment students' anxiety levels reduced substantially (2.60→3.60). This suggests that inquiry labs created a safe and supportive learning environment, giving students time and space to understand procedures, collaborate, and learn through trial and error. Minimal change occurred (2.63→2.70). Traditional instruction may maintain a high-pressure laboratory environment, leaving

anxiety levels largely unchanged. Chemistry treatment students showed strong reductions in anxiety (2.40→3.32). Because chemistry is often intimidating, inquiry-based instruction may have been particularly effective in making the subject feel less threatening. Again, minimal change occurred (2.42→2.50), reinforcing that the traditional approach is not effective for reducing student apprehension.

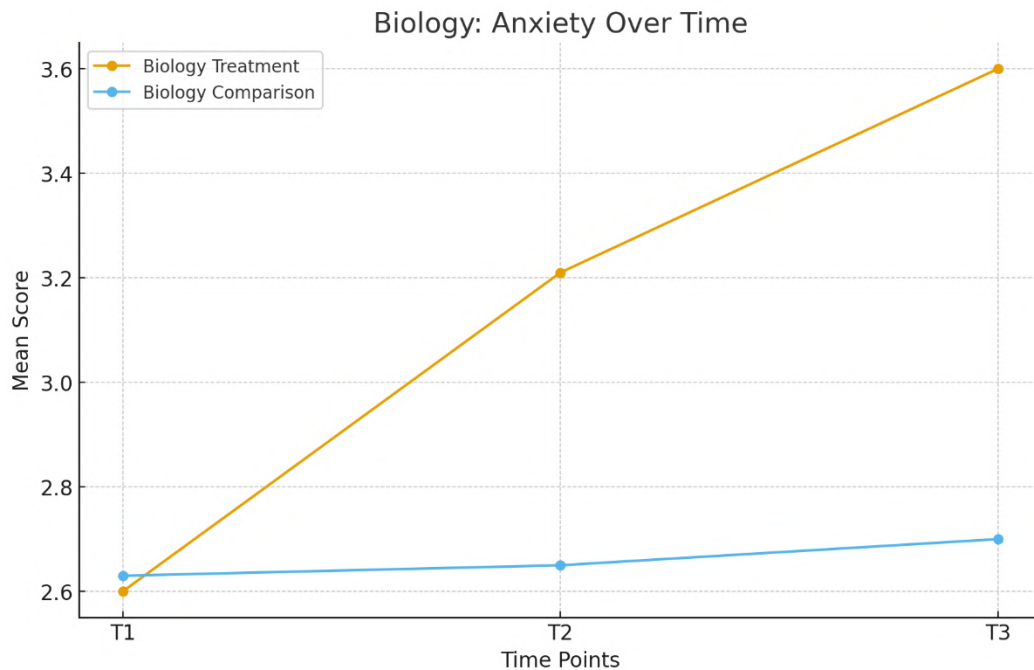


Figure 4.4a shows biology anxiety graph over time.

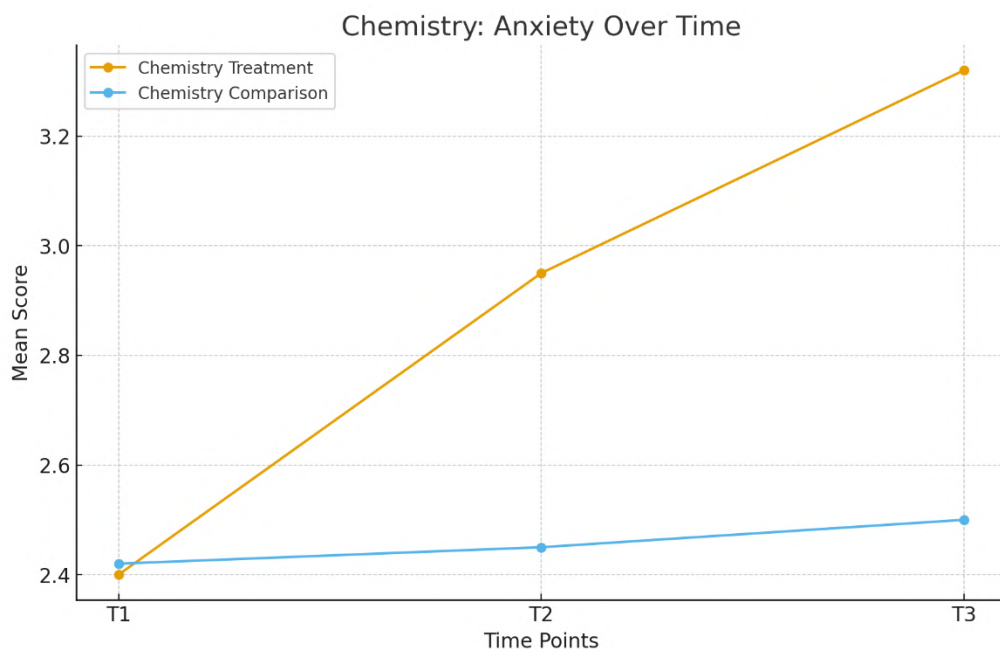


Figure 4.4b. shows chemistry anxiety graph over time.

Treatment group lines increase sharply, showing reduced anxiety. Comparison groups remain relatively flat. This demonstrates visually that inquiry-based instruction is far more effective in lowering science-related anxiety.

4.1.5 Career Interest

Group	Subject	T1 Mean	T2 Mean	T3 Mean
Treatment	Biology	3.00	3.48	3.88
Comparison	Biology	3.02	3.07	3.10
Treatment	Chemistry	2.75	3.25	3.60
Comparison	Chemistry	2.76	2.80	2.83

Career interest increased meaningfully (3.00→3.88). Inquiry-based labs likely inspired students by giving them a sense of real scientific engagement and helping them imagine themselves pursuing science careers. Small gains were observed (3.02→3.10), showing that traditional labs have limited influence on long-term motivation. The treatment group increased substantially (2.75→3.60). Practical, inquiry-based chemistry may have helped students see chemistry as an exciting and rewarding field. Minimal improvement (2.76→2.83) suggests traditional methods do not strongly inspire interest in future study or career paths.

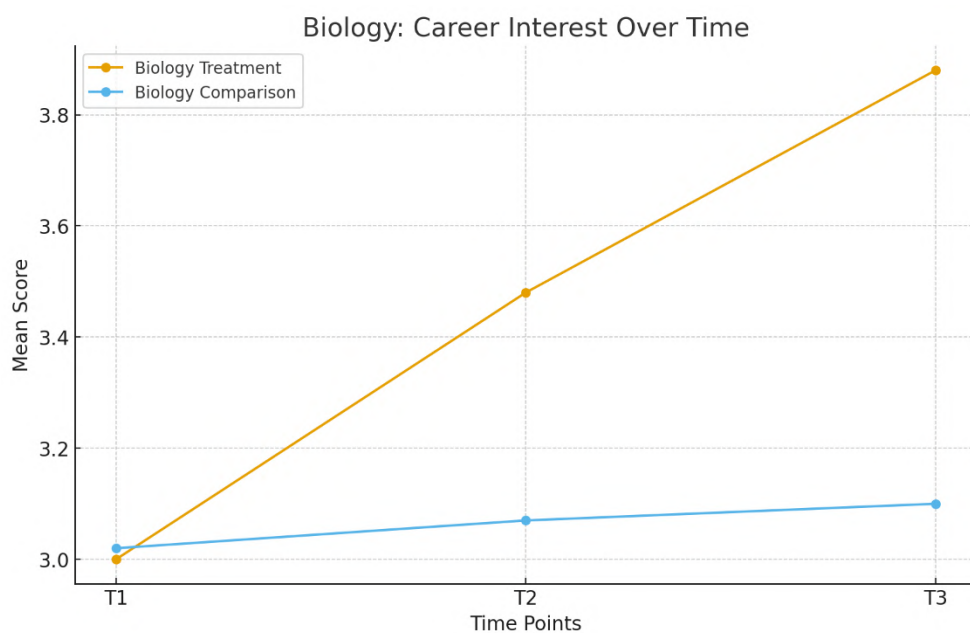


Figure 4.5a shows biology career interest graph over time.

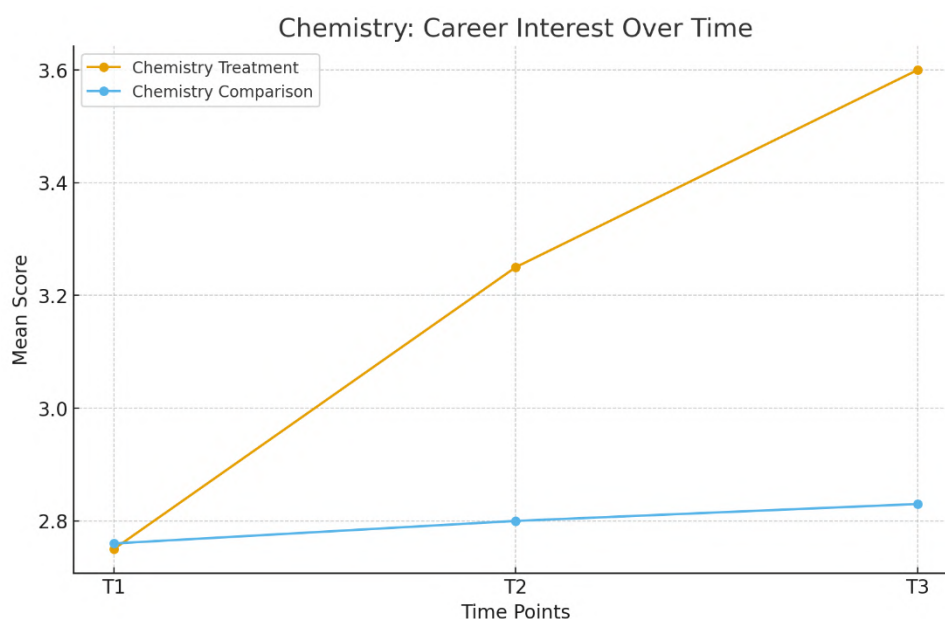


Figure 4.5b shows chemistry career interest graph over time.

Again, treatment groups show steep increases, while comparison groups remain nearly flat. This highlights the motivational potential of inquiry-based instruction in shaping career aspirations.

4.2 Discussion

The results of the present research are good indicators that investigational laboratory activities contribute positively to the attitude of students to Biology and Chemistry. In all the five attitudinal dimensions, including enjoyment, perceived value, self-efficacy, anxiety reduction, and career interest, the treatment groups showed significant improvement over the traditional laboratory counterparts. These are just some of the results that validate a large body of literature that underscores the motivational and conceptual advantages of active, student-centred laboratory teaching.

There is a substantial growth in fun among the treatment groups that are in support of research that inquiry-based classrooms help arouse curiosity, interest, and engagement with learning science (Yeung et al., 2011). Inquiry activities engage the learners in the process of a real science process, making them ask questions, take notes, and create meaning. In their argument, Mathias (2014) states that active learning methods enhance a higher level of cognitive engagement leading to increased enjoyment as learners will feel that they are more involved in the learning process. The small gains in the traditional groups, however, point to the fact that structured laboratory activities are insufficient to make enjoyment, which is evidence that procedural, teacher directed experiments are less effective in creating enthusiasm.

Perceived value was also very much facilitated in the inquiry based groups which means that the students were becoming more aware of the applicability and practical use of scientific concepts. This is in line with the findings by Ural (2016) that guided-inquiry laboratory experiences assist students to learn how science is related to their everyday life, and future career. Hands-on and exploratory instruction makes the difference so that the students can internalise the concepts and see science as meaningful. In the same manner, Cleveland, Olimpo and DeChenne-Peters (2017) discovered that active learning techniques in introductory biology courses enhanced student attitude and conceptual knowledge since it promoted a feeling of ownership of the learning process and

cultivated a sense of purpose. The small differences observed in comparison groups indicate that the conventional methods in the laboratory might not be sufficient to contextualise the scientific content.

The positive gains observed among the treatment groups in self-efficacy were found to be strong and this confirmed the already established linkage between active learning environment and increased confidence in the ability to perform laboratory tasks. Narueponjirakoon and Eamoraphan (2018) also found that the level of self-efficacy was higher among students who were introduced to inquiry-based chemistry laboratories compared to students who were introduced to traditional ones. The methods of inquiry offer a repeat experience to engage in genuine work, to collaborate, and to learn by trial and error which are some of the most important motivators of self-efficacy. Vishnumolakala et al. (2017) also argue that students acquire competence and self-confidence upon active working on scientific problems that support the high gains in this study. In the comparison groups, in turn, the improvements were not much, which supports the idea that the teacher-guided laboratory activities do not contribute to confidence-building to the full extent since students are not so engaged in decision-making and independent problem-solving.

Other prominent findings were anxiety reduction. The students of chemistry, especially, demonstrated significant reduction of anxiety in the treatment group. This is consistent with Ural (2016) who established that inquiry-based laboratory teaching methods improve anxiety levels by creating a positive, supportive, and student-focused learning atmosphere. Moreover, Drey (2019) discovered that active learning exercises, including STEM camps and hands-on interventions, have a decreasing effect on student anxiety and boost motivation since they create a positive environment where errors are considered normal as a way of learning. Similar results were noted by Hammill (2010) who found that student apprehension in veterinary anatomy labs decreased when they were taught with the focus on hands-on exploration, but not on procedural accuracy. Comparatively, the conventional groups used in the current study recorded nearly no decrease in anxiety implying that standard laboratory designs could possibly continue or even enhance the fear of failure.

The treatment groups also showed an impressive rise in the interest towards the career, which suggests that inquiry-based laboratories can have an impact on long-term goals. The exposure to real scientific research would aid students to develop positive attitudes towards scientific subjects, which would further raise their chances of thinking about employment in the field of science. According to Drey (2019), immersive STEM also increased student motivation and desire to continue on an academic and professional career trajectory related to science. Inquiry based settings seem to establish a home warmer atmosphere of inspiration that allows the students to project themselves into a scientific position. The fact that the small gains were observed in comparison groups supports the notion that the traditional laboratory set-ups are not capable of stimulating the same degree of inspiration or engagement required to impact career intentions.

These interpretations are supported by the mixed ANOVA findings which show that there are significant interaction effects between group type and time that inquiry-based laboratory instruction not only enhanced the attitudes but did so with higher rate and consistency than the traditional approaches. Yeung et al. (2011) observe that to achieve successful laboratory learning, the learning experience should incorporate active learning, reflection, as well as team-work, which is provided within inquiry-based learning environments. Inquiry-based experiences are cumulative which was also likely the contribution towards progressive improvements observed in this study.

The attitudes of students improved further as they got familiar and confident in the way of utilizing scientific practices.

Differences that were discipline specific were also notable. Students with higher post-test scores were the ones in Biology and those with greater relative improvements were the ones in Chemistry, in terms of anxiety reduction and self-efficacy. It is associated with the results of Penn and Ramnarain (2019), who have discovered that students tend to view chemistry as a more challenging and abstract science and, therefore, value active, inquiry-based learning that enables them to simplify the concepts through practical research. The significance of creating learning experiences that mitigate affective obstacles in science and anxiety, as well as, low confidence is also pinpointed by Wineinger, Fry and Moore (2022).

On the whole, the present research outcomes correspond in many ways with the modern literature and prove that inquiry-based laboratory teaching is much more effective than conventional laboratory teaching in boosting student attitude to Biology and Chemistry. Inquiry-based learning facilitates pleasure, perceived value, self-efficacy, anxiety, and career interest. These are vital affective results, which do not merely lead to an immediate success in the learning process, but also to the persistence in STEM disciplines.

4.3 Summary

This chapter showed the results of the research on the effects of the inquiry based laboratory activities on student attitudes towards Biology and Chemistry, analysed and discussed the results. The quantitative findings showed significant positive changes in all the five attitudinal dimensions including enjoyment, perceived value, self-efficacy, anxiety reduction, and career interest among students that received inquiry-based laboratory instruction. Conversely, little improvements were achieved with students who were taught by traditional technique of laboratory work. These differences were found to be significant with inferential statistics involving mixed ANOVA outcomes, which demonstrated the existence of these differences through time and across groups. Graphical presentations illustrated clear upward trends for treatment groups compared to comparison groups, further highlighting the positive and cumulative effect of inquiry-based learning environments. Biology students showed higher overall attitudinal scores at post-test, while Chemistry students exhibited larger relative improvements, particularly in anxiety reduction and self-efficacy. These discipline-specific differences support the idea that inquiry-based approaches are particularly beneficial for subjects often perceived as challenging or abstract.

The discussion synthesised these findings with existing literature, demonstrating strong alignment with prior research supporting the effectiveness of active learning and inquiry-based laboratory strategies in fostering positive affective outcomes. The chapter also highlighted the importance of student-centred learning environments in improving attitudes and increasing interest in science-related careers. Overall, the results provide compelling evidence for the integration of inquiry-based laboratory instruction into secondary and tertiary science curricula to support both immediate and long-term student engagement in STEM disciplines.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

The chapter shows the conclusion, the summary, and the recommendations of the research done to determine the effects of the hands-on, inquiry based laboratory activities on student attitudes towards Biology and Chemistry. It summarizes the major conclusions of Chapter Four and discusses the objectives of the research. It also provides some practical suggestions to educators, curriculum developers and policymakers and provides future research directions. The chapter is divided into four significant parts, including an introductory summary, an overview of the key findings, conclusions of the research and the recommendations of the study outlay.

5.1 Summary

The research was to address the impact of inquiry based laboratory activities on student attitude towards Biology and Chemistry. Five dimensions of attitude analyzed included enjoyment, perceived value, self-efficacy, reduction of anxiety and career interest. The data collected at three intervals by two different groups, including individuals who received inquiry-based laboratory training and participants who received the traditional methods of working with the laboratory, was analysed to define the patterns and trends over time.

The results revealed that the inquiry-based laboratory teaching led to significant positive changes in the five aspects of attitudinal dimensions. There was a significant addition of enjoyment in the treatment groups, and this is showing that active and exploratory learning conditions enhance more engagement. Both Biology and Chemistry have gotten a perceived value which, in turn, presupposes that students started to consider both subjects more applicable and relevant to their personal as well as academic lives. Self-efficacy was significantly improved among inquiry based learners, which demonstrates increased confidence in their capability of doing and mastering laboratory assignments. There was a significant reduction in anxiety levels especially in the Chemistry where the supportive and student-centred environments play a significant role in alleviating fear or intimidation, which is commonly experienced during laboratory work. The career interest in the treatment groups was also rising significantly and it is possible that positive experiences could affect the future educational and career choices. Comparatively, learners in the comparison groups who got the traditional laboratory teaching only had slight or moderate changes in these dimensions. The findings as a whole, present solid reasons to believe that inquiry-based laboratory teaching is more efficient than the traditional approach in creating a positive attitude of students towards science.

5.2 Conclusions

According to the findings of the current study, it is possible to make a number of conclusions. The most notable finding is that inquiry based lab training is a workable methodology used in enhancing student attitude towards Biology and Chemistry. Students who took part in inquiry activities showed to be more interested, they realised the worth of the subject material in a deeper manner, they felt more confident about doing the lab work, less anxious and more interested in seeking a career in science related field. Such advantages indicate that inquiry-based laboratories are not only effective to ensure one-time learning but also to ensure long-term interest and motivation.

It is also revealed in the findings that traditional laboratory teaching, being organized and predictable, is not enough to foster the attitudinal development. The limited improvement in the comparison groups on all attitude subscales demonstrated that passive or highly guided laboratory activities might not have the required factors to help develop curiosity, autonomy, and confidence in students. This brings out the fact that instructional means other than mere exposure in a laboratory, is one of the most dominant determinants of attitudinal change. Inquiry-based teaching encourages engagement, problem-solving, and thinking which are key ingredients of fulfilling learning processes.

The other finding that was made through the study is that inquiry-based learning facilitates psychological comfort during laboratory learning. The decreased anxiety level among the students in the treatment group especially in the Chemistry course indicates that inquiry-oriented activities are useful in establishing a conducive environment in which the learners are encouraged to explore, error and learn. Such climate encourages the emergence of scientific identities and the long term interest to STEM. Further, the research findings demonstrated that inquiry-based teaching is effective with the Biology and Chemistry students, but with the latter, the relative improvement is more significant. This shows that inquiry-based teaching can be especially supportive in the subjects of perceived abstractness or difficulty.

Lastly, inquiry-based laboratory teaching has a future implication on curriculum and classroom practice. Since the attitude is a key determining factor in motivation, participation and performance, the integration of inquiry methods could have a positive impact on the learning process in students. The results highlight that the process of teaching laboratory needs to be based not only on technical skills but on considerate pedagogical approaches that focus on student interaction and independence.

5.3 Recommendations

In the light of the research findings and conclusions of the present study, some recommendations are given on how the attitude and motivation of students can be improved in studying science. It is suggested that inquiry-based laboratory teaching should be adopted by schools, colleges and universities on a comprehensive basis by incorporating such work throughout the curricula in both the Biology and Chemistry courses. In order to implement it effectively, the science teachers are to be provided with the professional development which would be based on the inquiry-based strategies, scaffolding techniques, designing experiments, and facilitating strategies aimed at students. The activities in the laboratories must be structured in ways that encourage independence and discovery of students where the learners will be able to make their own decisions and develop hypotheses, construct experiments and formulate conclusions instead of just going through procedures. Moreover, it is important to establish conducive learning conditions that minimize anxiety among students; this may be done by encouraging students to learn together, give positive feedbacks and give them a chance to revise in order to give the students confidence. The inquiry-based strategies are also to be utilized in order to stimulate interest in the STEM professions, enabling the students to imagine the real-world practice in Biology, Chemistry, and other similar areas. The available laboratory teaching handouts and manuals must be checked and updated to incorporate the use of variations on inquiry that would promote critical thinking and creativity. It is advisable to continuously evaluate the student attitudes to track the effectiveness of the instructional methods and make the required changes. Lastly, future studies are recommended to investigate the inquiry-based learning in other levels of

education, compare virtual and real physical inquiry laboratories, examine long-term retention and conceptual learning, and gender and demographic variations in attitudinal change.

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ARTICLE 15

FORMING THE FUTURE PAN-AFRICAN LEARNER THROUGH TRANSFORMATIVE STEM: BRIDGING IDENTITY, INNOVATION, AND SUSTAINABILITY FOR AGENDA 2063

Kalungwishi Elijah Kabemba

elijahkalungwishi@gmail.com

University of Zambia, Zambia

Abstract

The COMSTEDA22 theme, *“Reimagining STEM for a Pan-African Future,”* aspires to bridge education, innovation, and sustainable development towards Agenda 2063. However, this paper, grounded in the GPS–DALE Macrophage framework, argues that the theme is **semantically overloaded¹ and risks reversing the authentic logic of transformation by prioritizing system-level adjustments over human formation.** Focusing on *Justice, Competence, Conscience, Unity, Sovereignty, Healing, Spirituality, and Morality*, the GPS–DALE Macrophage² framework conceptualizes STEM reform as a **pedagogical immune response³**, rather than a technocratic fix. It positions the **African learner** as the **regenerative core⁴** of transformation epistemically sovereign, spiritually grounded, and morally awakened.

Drawing on African epistemological perspectives (*Ubuntu⁵, Sankofa⁶*), cognitive load theory⁷ and the **DALE Matrix⁸**, the paper builds its arguments using findings from summative Senior Secondary STEM exam papers across Zambia (2000–2024), Ghana, Kenya, Rwanda, Uganda, and South Africa. These findings reveal a systemic over-reliance on low-order skills, limited alignment with **Agenda 2063⁹** and **SDG4¹⁰**, and minimal attention to learner agency, innovation, or continental consciousness. Using the lens of **18 diagnostic clusters¹¹** drawn from the GPS–DALE Macrophage framework, the paper analyzes all five COMSTEDA sub-themes and proposes a reframed theme: *“Forming the Future Pan-African Learner Through Transformative STEM,”* in which reform begins with the **soul of learning**, not merely the **shell of structure**. Moreover, **diagrams, cognitive heatmaps¹², and healing rubrics¹³** are referenced as tools to regenerate **African learning ecosystems¹⁴**. Ultimately, the GPS–DALE Macrophage framework empowers learners not merely as STEM participants, but as ethical architects of Africa’s sovereign future.

Note: This critique addresses all five COMSTEDA sub-themes, offering insights aligned with Decolonization, Innovation, Gender Equity, Climate Resilience, and Policy Harmonization.

1. Introduction

The 22nd Conference on Mathematics, Science, and Technology Education in Africa (COMSTEDA 22) sets out to mobilize STEM education as a strategic instrument for achieving the African Union’s Agenda 2063. However, the current framing of the theme reveals tensions between structural ambition and cognitive clarity. It signals a future-oriented STEM agenda but does not explicitly define the agent of that future. This paper responds to this ambiguity by revisiting the educational philosophy embedded in African identity and examining the logical order of reform. ***The foundation of any meaningful transformation must begin with the formation of the African learner as the Future Pan-African.*** This critical reflection engages African epistemological frameworks¹⁵, cognitive load theory, and semantic clarity to propose an alternative structure for STEM reform aligned with the continent’s developmental ethos.

2. The Problem of Semantic Overload

The current COMSTEDA22 theme is conceptually dense. It attempts to encapsulate educational reform, technological innovation, and sustainable development in one sweeping phrase. From a cognitive load perspective, this produces a 40% high level of intrinsic complexity that overwhelms the average stakeholder as illustrated in **Figure 1** and **Table 1** below. Sweller (1988) emphasizes that intrinsic load should be managed by segmenting and sequencing. Yet, this theme offers no such cognitive scaffolding. Instead, it fuses the '*what*,' '*how*,' and '*why*' of STEM reform into a single directive.

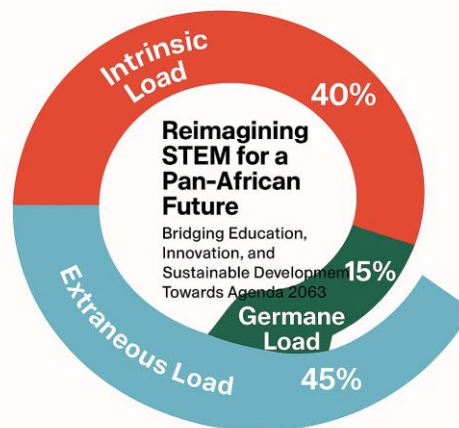


Figure 1: Cognitive Load Distribution of the COMSTEDA22 Theme

This figure analyzes the COMSTEDA22 theme: “Reimagining STEM for a Pan-African Future” using cognitive load theory to quantify its semantic and conceptual demands. The visual shows that the theme imposes a high extraneous load (45%), primarily due to layered policy jargon and abstract phrasing; intrinsic load (40%) arises from the conceptual complexity of simultaneously reimagining STEM, projecting futurism, and situating it within Pan-African ideals. Only 15% of the theme’s cognitive demand contributes to germane load, the portion that facilitates actual understanding and schema development for learners or policymakers. This load pattern supports the paper’s argument that the theme, while visionary, may overwhelm comprehension and hinder actionable reform without clearer human-centered grounding.

Practically, this presents difficulties in curriculum design, paper submission framing, and workshop facilitation. Stakeholders are likely to interpret the theme through fragmented lenses, risking incoherence in implementation. A well-structured theme should enable both conceptual clarity and pedagogical alignment being qualities this version struggles to achieve.

Table 1: Explanation of Cognitive Load Types

Cognitive Load Type	% Weight	Explanation
Intrinsic Load	40%	The theme involves inherently complex topics: STEM, Pan-Africanism, Education, and Development across sectors.
Extraneous Load	45%	The overload is high due to policy layering, vague wording, competing agendas, and lack of epistemic clarity.
Germane Load	15%	While some parts encourage deep learning (e.g: Equity, Innovation), much of the structure blocks long-term metacognition.

3. Ambiguity in the Verb 'Reimagining'

The term '**reimagining**' invites an act of mental reconstruction, yet offers no anchor point for where the original imagination began. Was STEM previously imagined through colonial frameworks? Perhaps through Post-independence educational reforms? Or alternatively through neoliberal donor-driven agendas? Without **epistemological specificity**¹², '**reimagining**' risks becoming **performative**¹³ as Ngũgĩ wa Thiong'o (1986) argues that the politics of language and naming in education cannot be ignored. To truly reimagine STEM in Africa, one must first name and deconstruct the foundational logics that informed the original design. Otherwise, the process may produce **aesthetic revisions**¹⁴ without substantive transformation. Re-imagination must therefore be grounded in historical consciousness, cultural memory, and ideological purpose.

4. Systems vs. Consciousness: A Reversal of Logic

The logic implied by the theme is that reforming STEM systems will yield Pan-African futures. This paper contests that sequence. As Cheikh Anta Diop (1987) asserts, African renewal begins with cultural and intellectual liberation. It is decolonized minds, but not reengineered systems that birth sustainable futures. Systems can only reflect the consciousness of those who create them. In this regards, Ghana's pilot projects using local languages like Twi and Ewe for science instruction at the primary level (Kwame Nkrumah University, 2016) demonstrated that students developed stronger conceptual understanding and cultural ownership of STEM topics. These reforms succeeded not by changing systems alone, but by shifting learner consciousness and epistemic frameworks as shown in Figure 2 below.



Figure 2: Logics of Pan-African Transformation – From Imagining People to Designing Systems and Creating the Future

This diagram illustrates the GPS–DALE Macrophage's regenerative philosophy for African STEM reform. It begins with reimagining people as the drivers of epistemic healing, proceeds to the ethical design of systems that reflect indigenous values and justice, and culminates in creating a future anchored in sovereignty, innovation, and continental identity. The flow challenges the reversal of priorities that places structure above soul.

Therefore, the **Future Pan-African** must be formed first through pedagogy, history, language, and ethical grounding. Only then will that individual possess the capacity to reform systems in ways that are authentically African and developmentally relevant. Ignoring this order risks producing **technocratic adjustments** that leave colonial logics intact.

5. The Philosophical Imperative: People Before Structures

African philosophical traditions emphasize communal identity, ancestral wisdom, and ethical stewardship. **Ubuntu** and **Sankofa** offer a pedagogical grounding that contrasts sharply with mechanistic system-first approaches. Ubuntu teaches that the individual is constituted by the community (Ramose, 2002), while Sankofa commands us to retrieve what was left behind (Temple, 2010; Okrah, 2003). Besides, Samir Amin (2006) reinforces this in arguing that no structural transformation can be successful unless preceded by **ideological reorientation**¹⁵ of people who are self-consciously

African. When we begin with structures, we risk retrofitting old colonial objectives with new Pan-African labels.

As conceptualized by Ramose (2002), Ubuntu views the self as inseparable from the community, while Sankofa, rooted in **Akan philosophy**²², emphasizes the recovery of past wisdom to build forward (Temple, 2010; Okrah, 2003). These philosophies are not merely rhetorical references. Ubuntu informs the GPS-DALE Macrophage metric on communal competency and ethical leadership, while Sankofa directly guides the recovery of indigenous evaluation approaches. In the GPS-DALE Macrophage evaluations, these principles are embedded into rubrics that assess not only correctness but also historical and cultural relevance.

6. Pedagogical Reframing: From Systems Thinking to Learner Formation

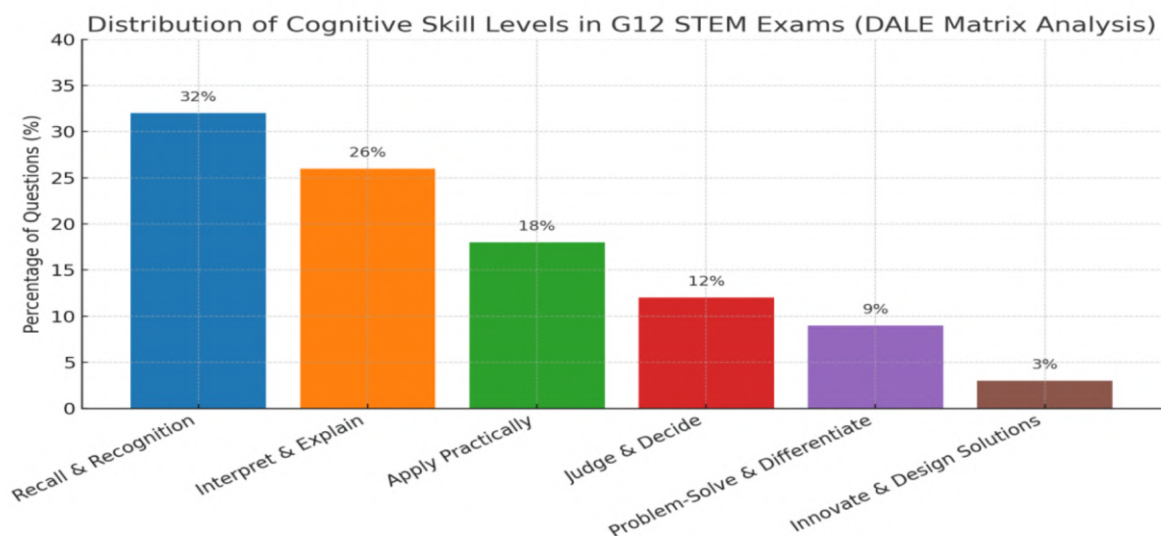


Figure 3: Distribution of Cognitive Skill Levels in 2000–2024 ECZ Grade 12 STEM Exams (GPS–DALE Macrophage Matrix Analysis)

This chart highlights the imbalance in question design favouring lower-order skills across analysed STEM exams.

This figure illustrates the classification of G12 STEM examination questions according to the six cognitive levels defined in the *Zambian Modified Bloom's Taxonomy (Z-M BT)*: (1) Recall and Recognition, (2) Interpret and Explain, (3) Apply Practically, (4) Judge and Decide, (5) Problem-Solve and Differentiate, and (6) Innovate and Design Solutions. Derived from the DALE Matrix diagnostics, the distribution reveals a significant clustering in the lower-order domains particularly Recall and Recognition while higher-level competencies such as Innovation, Problem-Solving, and Judgement are sparsely represented. This pattern underscores the need for epistemically regenerative assessment tools aligned with *SDG4*, *Agenda 2063*, and the pedagogical immune response logic of the GPS–DALE Macrophage framework.



Figure 4: Conceptual Flow of Learner-Centred Transformation in STEM Reform

This visual reinforces the argument that systems reform must follow identity and consciousness formation.

This visual outlines a three-step regenerative pathway to authentic Pan-African STEM reform. Step 1 begins with forming the Pan-African learner through identity, ethics, and cultural memory. Step 2 involves system design that reflects these values—shaping curriculum, pedagogy, and assessment through a justice-centered lens. Step 3 delivers transformed STEM outcomes aligned with Agenda 2063, innovation, and sustainability. The flow affirms that lasting reform must be learner-driven, not system-imposed.

This flow diagram embodies the Macrophage philosophy of healing through educational sequencing. True reform begins not with institutional rearrangement but with the soul of the learner memory, moral grounding, and epistemic sovereignty. These internal drivers trigger a system design response (curriculum, pedagogy, diagnostics), which in turn activates sustainable, innovative STEM futures. The figure shows how healing the learner’s core enables immune-strengthening of the whole education system.

The shift from system reform to learner formation demands a new pedagogical architecture. Consequently, STEM must not merely teach skills for employment, but cultivate identity, agency, and innovation rooted in African realities. Instruments like the “GPS-DALE Macrophage” Matrix that we use in our Multiple Research Evaluations; provides tools for assessing whether exam questions, lessons, and learning outcomes align with National and Continental Aspirations. This matrix connects Bloom’s Taxonomy to Zambia’s NDPs, SDG4, Africa 2063 goals and numerous African Frameworks and Protocols. Such frameworks re-center the learner as the focus of STEM, not just as a recipient of content but as a builder of African futures.

Since 2024, Mr. Kalungwishi Kabemba, an educational researcher from Zambia, affiliated with the School of Education, Department of Mathematics and Science is investigating on how to introduce the GPS-DALE Macrophage-aligned rubric to evaluate any educational Question at any level of Education in Zambia and Africa at large. This framework has helped the researcher to map question types to National Development goals and Bloom’s levels, revealing that over 60% of questions failed to assess higher-order problem-solving or 21st-century skills. The project underscores the need for learner-centric reforms rather than assessment-driven adjustments alone (DALE Evaluation Report, 2024). The DALE Matrix includes a three-tier diagnostic structure: Tier 1 (Recall/Procedural), Tier 2 (Application/Relational), and Tier 3 (Critical/Evaluative). Each level maps to Bloom/Zambia-Modified Bloom’s Taxonomy (Z-M BT) categories and DALE policy links, providing a multi-dimensional view of how exam questions stimulate cognitive growth.

To translate these frameworks into actual classroom impact, policy alignment must be accompanied by teacher-level capacity building. Curriculum reforms anchored on the GPS-DALE Macrophage findings should be paired with training programs that help teachers recognize multi-tier question types, cognitive load levels, and Bloom’s /Zambia-Modified Bloom’s Taxonomy targets. Without this translation, national policies risk stalling at the document stage.

The simplified DALE Matrix rubric in Table 2 is designed to help Ministries of Education, ECAs, and educators diagnose the quality of STEM exam items using the GPS–DALE Macrophage framework. Each field evaluates alignment to transformative African learning goals.

Table 2: Simplified DALE Matrix Rubric for STEM Evaluation

DALE Field	Low (1 pt)	Medium (2 pts)	High (3 pts)	Evaluator Prompt
Cognitive Demand (Z-M BT)	Recall only	Some analysis	Creative reasoning	Does the question go beyond memory or routine?

DALE Field	Low (1 pt)	Medium (2 pts)	High (3 pts)	Evaluator Prompt
Tier Structure (Z-M BT)	Single-Tier	Two-Tier	Multi-Tier	Does the question build across levels of thought?
Skill Type Assessed	Procedural only	Conceptual	Metacognitive	What skill does the learner demonstrate or build?
Contextual Relevance	Foreign context	General setting	Local/Africanised	Is the question framed in a relatable African context?
SDG4 & Agenda 2063 Alignment	No alignment	Implicit alignment	Explicit alignment	Does it promote Africa's educational/development goals?
Learner Agency Required	Passive role	Guided action	Full agency	Must the learner think independently or take decisions?
Epistemic Sovereignty	None	Partial	Affirmed	Does it reflect Africa's own knowledge and logic?
Policy/Competency Mapping	Unclear	Indirect	Direct	Is the question traceable to a clear curriculum goal?

How to use: Score each field from 1 to 3 based on the question. The total score (out of 24) guides intervention:

- a) 18–24 = High-quality transformative item
- b) 12–17 = Needs minor refinement
- c) 6–11 = Major revision needed
- d) Below 6 = Reconsider question purpose

7. Towards a Better Theme: A Proposed Reframed Theme

The current theme could be revised for clarity, agency, and pedagogical depth. This paper proposes: **'Forming the Future Pan-African Learner Through Transformative STEM: Bridging Identity, Innovation, and Sustainability for Agenda 2063.'** This rephrasing foregrounds the learner (**'Future Pan-African'**), specifies the tool (**Transformative STEM**), and makes explicit the developmental objective (**Agenda 2063**). It also harmonizes identity with innovation, ensuring that the digital and economic ambitions of Africa are built on cultural foundations. It is only through identity-centered transformation that Africa can escape dependency on borrowed models of growth.

8. Visual Logic and Empirical Foundations

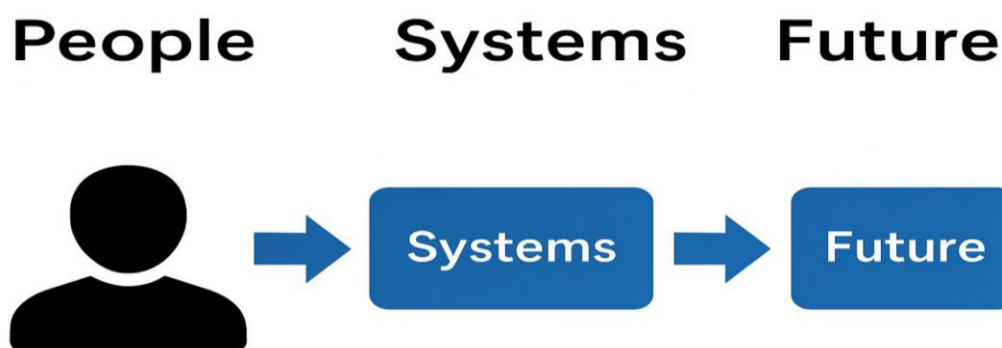


Figure 5: Reversing the Logic of Reform – From Systems to Souls to Sovereignty

This diagram visually illustrates the core critique of the COMSTEDA22 theme: that meaningful STEM transformation in Africa must begin with the learner (people), not systems. The flow moves from individual epistemic healing (souls), through empowered pedagogy, and finally toward

systemic sustainability and future-readiness. It challenges technocratic reforms that bypass identity, morality, and agency.

8.1 Methodological Framing of Empirical Insights

The empirical illustrations referenced throughout this critique are drawn from a longitudinal document analysis of selected 2000-2024 ECZ Grade 12 STEM examination papers and some across multiple African education systems and IGCSE Cambridge.

Using the Descriptive Analysis and Learning Evaluation (DALE) Matrix framework currently under its validation stage, each exam paper was evaluated against cognitive demand, the Original Bloom’s taxonomy levels, the Revised Bloom’s taxonomy and the Zambian Modified Bloom’s taxonomy levels, 21st-century skills, and alignment with national and continental development priorities, such as Zambia’s national Development Plans (NDPs), SDG4, and Agenda 2063.

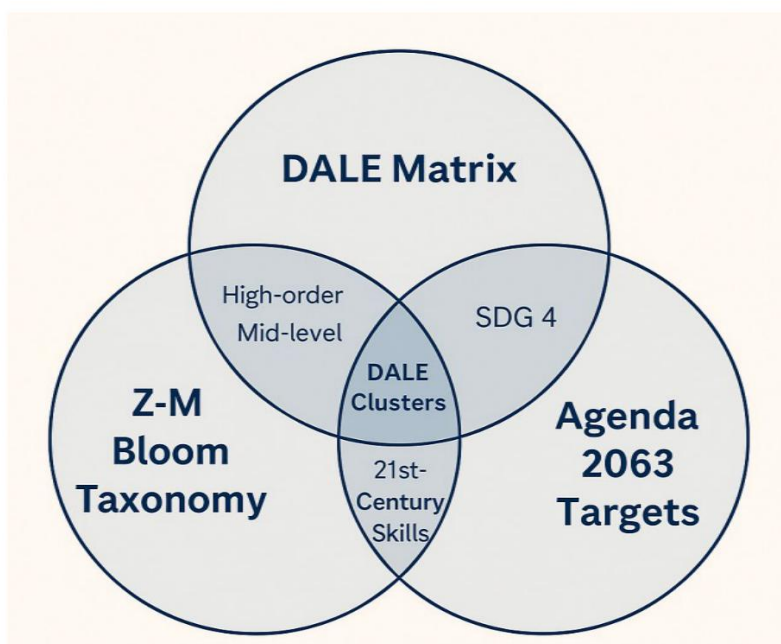


Figure 6: Integrative Relationship between Zambian Modified Bloom’s Taxonomy, the GPS–DALE Macrophage Matrix, and Agenda 2063

This diagram illustrates the conceptual relationship between cognitive complexity (Z-M BT), diagnostic pedagogy (DALE Matrix), and continental development priorities (Agenda 2063). The Zambian Modified Bloom’s Taxonomy provides a localized cognitive framework, while the GPS–DALE Matrix operationalizes it through diagnostic clustering. These are then aligned with broader Pan-African transformation targets. The intersection reveals how epistemic tools, when culturally adapted, can bridge classroom assessment with sovereign development agendas.

This Venn-style diagram maps the overlapping domains of three frameworks critical to African STEM reform. At the core, DALE Clusters serve as the central convergence of diagnostic pedagogy. Higher-order and mid-level cognitive skills form the shared space between the Z-M Bloom’s Taxonomy and the DALE Matrix. 21st-century skills define the intersection between Z-M BT and Agenda 2063. Meanwhile, SDG4 represents the shared developmental vision between Agenda 2063 and the DALE Matrix. The figure demonstrates how the GPS–DALE Macrophage model strategically bridges cognitive complexity, national diagnostic frameworks, and continental development targets.

Although the GPS-DALE Matrix is still pending formal rollout through institutional consultations with the University Of Zambia (UNZA) and the Ministry of Education, the initial analyses have

already revealed a consistent pattern of more than 60% of examined questions across STEM subjects disproportionately targeting lower-order recall and procedural skills.

These findings substantiate the central thesis of this paper that meaningful reform must shift from system-wide rhetoric to learner-centered transformation, with robust cognitive and developmental indicators embedded into curriculum and assessment design.

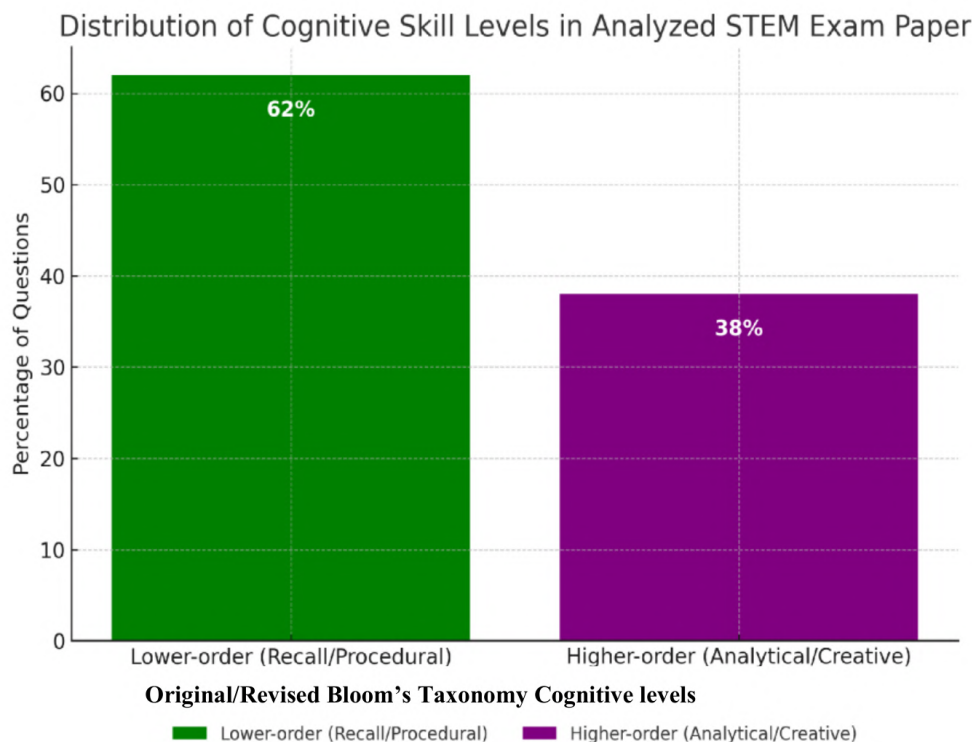
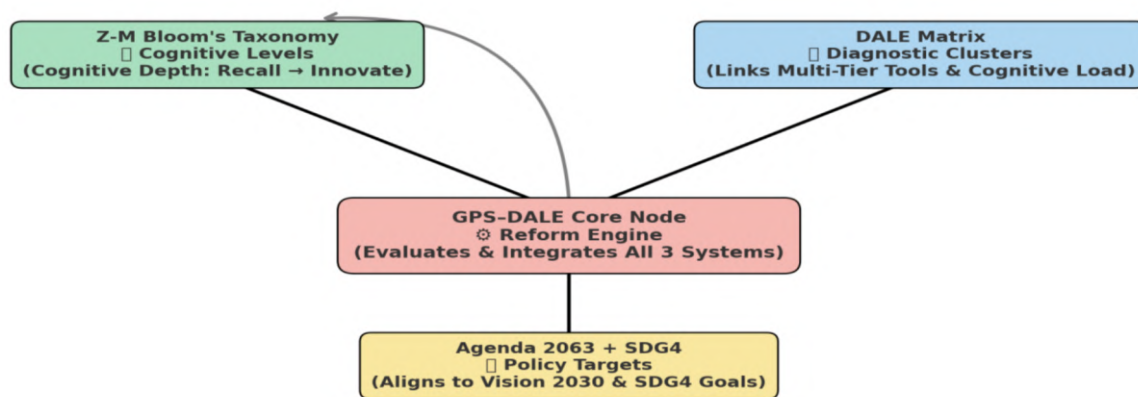


Figure 7: Grouped Distribution of Cognitive Skill Levels in Grade 12 STEM Exams (DALE Matrix Analysis)

This figure presents two grouped bar graphs illustrating the overall cognitive demands embedded in G12 STEM exam questions, based on *Zambian Modified Bloom's Taxonomy (Z-M BT)* levels. The data show a stark imbalance: over 60% (precisely 62%) of assessed items fall within the lower-order cognitive categories—namely, Recall and Recognition; Interpret and Explain; and Apply Practically. In contrast, only 38% engage higher-order skills such as Judge and Decide, Problem-Solve and Differentiate, and Innovate and Design Solutions. The figure visually affirms the DALE Matrix's diagnostic finding that most summative assessments privilege procedural knowledge and memory recall, thereby underrepresenting innovation, decision-making, and Pan-African transformative competencies required by Agenda 2063 and SDG4.

These bar charts visualize the proportion of lower-order versus higher-order questions across Grade 12 STEM exams, analyzed using the DALE Matrix framework. They emphasize the urgent need for transformation toward learner-centered and higher-order cognitive assessment.

Instruments like the “DALE” Matrix (Descriptive Analysis and Learning Evaluation), a policy-aligned analytical tool currently under its final development stage, provide a method for assessing whether exam questions, lessons, and learning outcomes align with national and continental aspirations. The GPS-DALE Macrophage Matrix connects Bloom's Taxonomy to Zambia's National Development Plans, SDG4, and Africa 2063 goals by evaluating each question's skill level, developmental focus, and policy relevance.



GPS-DALE creates a triangulated evaluation system linking Z-M BT cognitive levels, multi-tier diagnostic clusters, and global policy targets (Agenda 2063 & SDG4).

Powered by GPS-DALE Framework | Clustered Cognitive-Policy Analysis

Figure 8: Triangulated Evaluation System Linking Zambian Modified Bloom’s Taxonomy, DALE Matrix Diagnostic Clusters, and Agenda 2063/SDG4 Targets

This systems map illustrates how the GPS–DALE Macrophage framework forms a triangulated evaluation engine that connects cognitive depth, diagnostic pedagogy, and global policy goals. The Z-M Bloom’s Taxonomy establishes cognitive levels from basic recall to innovation. The DALE Matrix provides multi-tier diagnostic clusters aligned with cognitive load and skill types. These are processed through the GPS–DALE core node—serving as the reform engine—evaluating and integrating all three frameworks. The output is aligned with Agenda 2063 and SDG4 targets, promoting transformative, policy-relevant education. A feedback loop to Z-M BT ensures continuous recalibration. This dynamic integration reflects the immune-like adaptability of the Macrophage philosophy.

Figure 8 thus illustrates how the Z-M Bloom Taxonomy, the GPS-DALE Macrophage Matrix, and Agenda 2063 targets are integrated. Each GPS-DALE Macrophage cluster is mapped to cognitive levels (Z-M BT), 21st-century skills, and SDG4 targets, forming a triadic evaluation system for diagnostic and reformative use.

8.2 Illustrative Diagnostic Scenarios from the GPS–DALE Macrophage

- 1. Low-Order Saturation in Biology Exams (Zambia, 2023):** The DALE Matrix revealed that 75% of the questions in a Grade 12 Biology paper only assessed Tier 1 skills (recall and basic definitions). The GPS–DALE immune response triggered a curriculum alert, recommending integration of Tier 3 reasoning questions aligned with SDG4 Target 4.7.
- 2. Epistemic Mismatch in Physics Syllabi (Kenya):** A diagnostic scan showed heavy reliance on Western examples with no contextual grounding in African physics applications. The immune response initiated a “healing rubric” adaptation, encouraging teachers to include local innovations (e.g., borehole pumps or solar dryers) to affirm epistemic sovereignty.
- 3. Agency Deficiency in Chemistry Practical Exams (South Africa):** Learners were assessed only on procedural tasks without opportunities to reflect or hypothesize. The DALE analysis activated an immune flag and proposed a rubric shift toward Tier 3 items that promote learner agency and metacognition.

4. **Curriculum Toxins in STEM Textbooks (Ghana):** Thematic analysis exposed colonial-era narratives and gender biases. The GPS–DALE immune logic initiated regeneration by recommending culturally grounded diagnostics and justice-based textbook audits.
5. **Misaligned Question Formats in National Exams (Rwanda):** National exams focused on numerical solutions but lacked real-world application. The immune response redirected teacher training toward multi-tiered question construction and scenario-based assessments.

8.3 Sequence of Educational Transformation in Africa

The model below reflects the revised pedagogical logic proposed in the paper: meaningful reform begins with the epistemic realignment of the learner (People), which informs pedagogical systems (Systems), supported by evaluation instruments like the DALE Matrix, and ultimately drives sustainable development outcomes (Future).

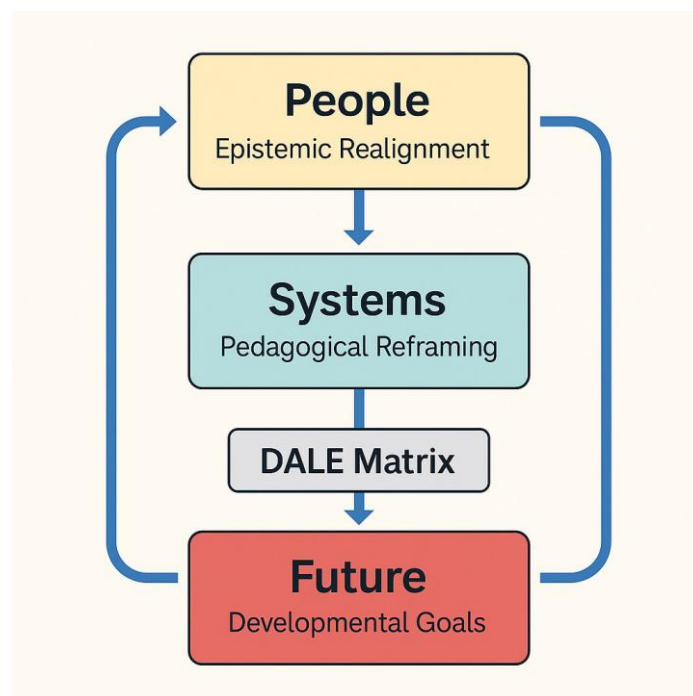


Figure 9: Sequence in Educational Transformation in Africa: From People to Systems to Development Goals

This diagram presents a transformative sequence essential to African education reform. It begins with people, emphasizing epistemic realignment and identity restoration. The second phase targets system-level redesign through pedagogical reframing using the DALE Matrix. The final phase aims at realizing future development goals, including SDG4 and Agenda 2063. This flow reflects the GPS–DALE Macrophage logic that authentic transformation starts with healing the learner’s mind and soul before restructuring systems or pursuing sustainability targets.

First, **form** the Future Pan-African as an individual grounded in heritage, ethics, and problem-solving capacity. Then, **design systems** such as curricula, pedagogies, and assessments that reflect this identity. Finally, these systems **will produce a sustainable Pan-African future** aligned with **Agenda 2063**.

This reversal from the current theme’s logic is essential to avoid hollow reforms. Without people-driven change, system reforms will lack soul. Figure 2 illustrates this spiral logic.

9. Sub-Theme Critique: Disconnect between Implementation and Thematic Integrity

Figure 10 presents the 12-petal schema used in the DALE Matrix to map the cognitive, pedagogical, and policy layers embedded in STEM education reform. Each petal represents a diagnostic cluster tied to critical dimensions such as identity formation, complexity of skills, SDG alignment, learner agency, and assessment equity. The petals are interlinked through the GPS–DALE Macrophage’s regenerative logic, symbolizing how reform is not linear but circular, recursive, and rooted in moral and epistemic sovereignty. The diagram serves as both a diagnostic compass and a healing map highlighting the multidimensional interactions between learning design, cognitive demand, and Pan-African development goals.

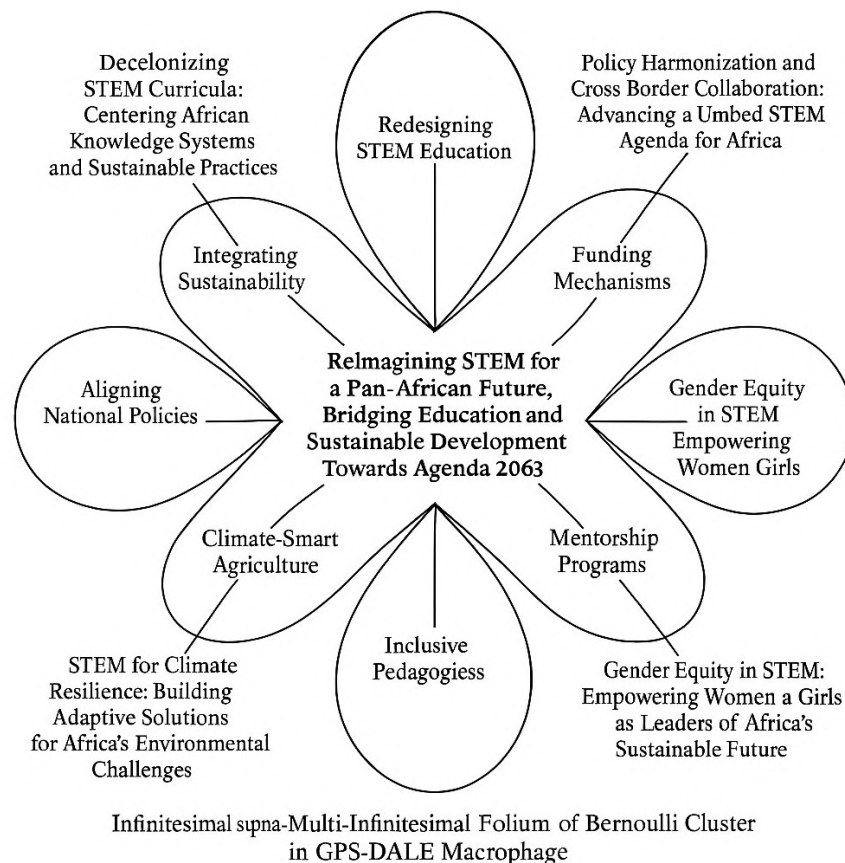


Figure 10: 12-Petal DALE Mapping of the STEM Reform Agenda

The following explanation interprets the symbolic 12-petal Bernoulli-style diagram presented in the visual titled 'Reimagining STEM for a Pan-African Future.' in Figure 10. Each petal corresponds to a GPS-DALE Macrophage -aligned thematic cluster, functioning as a regenerative node within the educational immune system. This mapping strengthens both diagnostic precision and reform alignment.

1. **Decolonizing STEM Curricula:** Activates the GPS-DALE Macrophage cluster on Ethical/Pedagogical Voice and Integration of African Philosophies (Ubuntu, Sankofa).
2. **Integrating Sustainability:** Aligns with 21st Century Skills (Sustainability, Adaptability) and policy-linked cognitive domains.
3. **Aligning National Policies:** Connects directly to the Policy–Practice Link GPS-DALE Macrophage cluster; reinforces Agenda 2063 and SDG4 alignment.
4. **Climate-Smart Agriculture:** Stimulates STEM relevance through climate adaptation by engaging cognitive application and resilience.
5. **STEM for Climate Resilience:** Merges sustainability with high-order cognitive tasks linked to Multi-tier Question Insight cluster.

- 6. Inclusive Pedagogies:** Promotes Equity, Access, and Agency directly aligned with Learner-Centered Framing and Ethical Voice.
- 7. Gender Equity in STEM:** Empowering Women and Girls: Maps to the GPS-DALE Macrophage cluster on Social Justice and SDG4.5 (inclusive, equitable education).
- 8. Mentorship Programs:** Supports skills development in Collaboration and Communication linked to the GPS-DALE Macrophage Skill Assessment logic.
- 9. Gender Equity in STEM (repeated):** Reinforces focus on gendered epistemic justice and leadership framing under Vision 2030 priorities.
- 10. Funding Mechanisms:** Supports implementation of pedagogical innovations, the GPS-DALE Macrophage training and teacher-level uptake.
- 11. Policy Harmonization:** Cross-border coherence is essential for scalable reforms tied to the GPS-DALE Macrophage Matrix's comparative utility.
- 12. Redesigning STEM Education:** Summarizes the core goal: transformative system renewal powered by learner-focused metrics like GPS-DALE Macrophage.

This petal-map mirrors the GPS-DALE Macrophage Matrix philosophy: reforms are not linear, but regenerative. Each petal is a policy-immune cell activated to restore educational justice, skill transfer, and learner dignity. Together, they uphold the vision of Agenda 2063.

9.1 Decolonizing STEM Curricula

While this sub-theme rightly calls for integrating indigenous knowledge and sustainable practices, it still centers curriculum systems rather than learners themselves. Without first transforming the epistemic identity²³ of the learner (see Ngũgĩ wa Thiong'o, 1986), integrating indigenous content risks being tokenistic²⁴ as merely adding local knowledge to existing structures does not decolonize learning. However, true epistemological shift must begin with the student's consciousness, language, and cognitive worldview. Therefore, even if this sub-theme were fully implemented, it would struggle to deliver a Pan-African future unless learners are formed first as Pan-African thinkers.

9.2 Pan-African Innovation Hubs

This sub-theme promotes entrepreneurship and digital innovation, but positions STEM as a vehicle for tech economies without grounding in Pan-African values. The risk is producing technically proficient but ideologically neutral graduates²⁵ who serve market systems rather than transforming them (Amin, 2006). Without embedding Ubuntu and de-colonial ethics into innovation, the future workforce may perpetuate dependency. Thus, innovation hubs must first form critical Pan-African minds before launching startups and scaling technologies.

Rwanda's engagement with international coding academies²⁶ as Andela²⁷ highlighted this disconnect. While graduates excelled in software skills, evaluations by the African Development Bank (2021) noted a lack of grounding in ethical innovation or community impact, raising concerns about exporting talent without transforming local systems or addressing Pan-African priorities.

9.3 Gender Equity in STEM

Empowering women and girls is essential. However, if equity is treated as numerical parity rather than identity and consciousness development, it risks liberal inclusion rather than structural transformation. As Diop (1987) points out, gender parity must be accompanied by cultural revalorization²⁸. STEM for African women must affirm indigenous leadership archetypes²⁹, not merely insert them into colonial frameworks. Therefore, gender equity alone will not yield a Pan-African future unless identity formation is central.

9.4 STEM for Climate Resilience

This sub-theme aligns with Africa’s environmental urgency, promoting renewable energy and adaptive systems. Yet, its emphasis on infrastructure may overshadow pedagogical transformation. STEM cannot solve climate issues with imported technological logic alone. Learners must first internalize stewardship ethics rooted in **African cosmologies**³⁰ (Sefa Dei, 2002). Otherwise, Africa will remain a consumer of global climate discourse. Thus, resilience must begin in the mind before the system. The Green Schools programme in South Africa, though focused on sustainability, faced criticism for importing Eurocentric models of environmental science without embedding indigenous ecological knowledge systems (Sefako Makgatho Climate Education Review, 2021). Learners could cite global emissions statistics, yet struggled to relate STEM learning to local land practices or ancestral conservation methods.

9.5 Policy Harmonization and Cross-Border Collaboration

Continental frameworks are crucial, but policy harmonization assumes systems can integrate top-down. Yet, as Sweller (1988) argues, cognitive load in learning increases when frameworks lack grounding in learner schemas. Policies without pedagogical identity³¹ risk bureaucratic convergence without transformation. Harmonization is only effective when built on a shared Pan-African learner identity. Therefore, systems alignment without people formation will not yield the Africa We Want.

9.6 Reconfiguring the COMSTEDA22 Sub-Themes through the GPS–DALE Macrophage Diagnostic Lens

Table 3 maps the five COMSTEDA22 sub-themes through the diagnostic lens of the GPS–DALE Macrophage framework, aligning each theme with core pedagogical concerns, Macrophage clusters, and values-based transformation priorities. It illustrates how rethinking reform from the learner outward can regenerate STEM systems toward Agenda 2063 and epistemic sovereignty.

Table 3: GPS–DALE Macrophage Reconfiguration of COMSTEDA22 Sub-Themes for Transformative STEM Reform

COMSTEDA Sub-Theme	Macrophage Focus	Core DALE Concern	Transformative Shift
1. STEM Curriculum	Bloom Levels, Detoxification	Overloaded, irrelevant frameworks	From topics to epistemic dignity
2. Inclusive Pedagogy	Assessment Violence, Equity, Identity	Gender and social bias in tools	From uniformity to epistemic justice
3. Indigenous Knowledge + Digital	Ubuntu Logic, Cognitive-Spiritual Balance	Loss of ancestral anchorage	From colonized code to cultural memory
4. Teacher Capacity	Load Theory, Reprofessionalization	Passive curriculum implementation	From delivery to diagnostic agency
5. Policy and Systems	Agenda 2063/SDG4 Alignment, Threshold Logic	Reform starts with structures, not learners	From structures to regenerative learning ecosystems

Sub-Theme 1: Reimagining STEM Curriculum for Relevance and Resilience

- Macrophage Cluster:** Curriculum Realignment, Bloom Rebalancing, Cultural Detoxification.
- Core Values Anchored:** *Justice, Competence, Sovereignty.*
- DALE Concern:** Overdependence on lower-order skills; weak Agenda 2063 alignment.
- Transformation Priority:** Relevance must emerge from epistemic dignity and African contexts.

Sub-Theme 2: Gender Responsiveness and Inclusive STEM Pedagogy

- Macrophage Cluster:** Equity Diagnostics, Hidden Curriculum, Assessment Violence.
- Core Values Anchored:** *Unity, Conscience, Morality.*

- DALE Concern:** Gendered assumptions in assessment rubrics and teaching.
- Transformation Priority:** Inclusivity begins with pedagogical identity and agency-centered diagnostics.

Sub-Theme 3: Integrating Indigenous Knowledge and Digital Innovation

- Macrophage Cluster:** Ubuntu Intelligence, Digital-Human Fusion, Indigenous Pedagogies.
- Core Values Anchored:** *Sovereignty, Spirituality, Healing.*
- DALE Concern:** Technological fixes often displace epistemic sovereignty.
- Transformation Priority:** Innovation must recover ancestral wisdom and spiritual knowing, not overwrite it.

Sub-Theme 4: Strengthening STEM Teacher Education and Professional Development

- Macrophage Cluster:** Professional Reorientation, Diagnostic Capacity Building, Cognitive Load Management.
- Core Values Anchored:** *Competence, Healing, Conscience.*
- DALE Concern:** Teachers are implementers of pre-digested curriculum, not co-creators of reform.
- Transformation Priority:** Empower teachers as pedagogical healers, not just deliverers.

Sub-Theme 5: Policy and Systems Transformation for Sustainable STEM

- Macrophage Cluster:** Policy Alignment Grid, Threshold Pass Analysis, Reform Sequence.
- Core Values Anchored:** *Justice, Unity, Sovereignty.*
- DALE Concern:** System-first models dislocate learners from the center of reform.
- Transformation Priority:** Policy must orbit around learner regeneration, not bureaucratic metrics.

10. Conclusion

The COMSTEDA22 theme, while inspirational in ambition, is both semantically overloaded and structurally misaligned with Pan-African epistemology. Initially, the critique established that the theme's logical flow of placing system transformation before learner formation reverses the principles of transformative education. Besides, further critique in Section 9 reveals a deeper problem of achieving a Pan-African future. Even if each sub-theme is implemented in full, the overarching goal of achieving a Pan-African future remains unreachable. This is because the sub-themes, while individually relevant, do not converge on the central problem of agency. Instead, they propose structural, economic, or policy-level interventions without first forming the kind of Pan-African consciousness necessary to drive and sustain those reforms. Therefore, the failure lies not in the ambition of the theme, but in its philosophical sequence. Africa does not need to “reimagine STEM” in the abstract, but it needs to form the Pan-African mind that will reimagine, redesign, and rebuild the continent’s future. Hence, this paper proposition of 'Forming the Future Pan-African Through Transformative STEM: Bridging Identity, Innovation, and Sustainability for Agenda 2063.' This must be the new foundation of any COMSTEDA or STEM reform effort aligned with Agenda 2063.

In conclusion, while the COMSTEDA 22 theme articulates a bold vision for the continent, it embeds a flawed philosophical order. By prioritizing the reimagining of systems over the formation of consciousness, the COMSTEDA22 theme risks reinforcing technocratic interventions that fail to emancipate as many national curricula remain infused with latent curriculum toxins³³, subtle remnants of colonial logic and uncontextualized pedagogies that obstruct authentic learner empowerment. Furthermore, the persistent dominance of recall-based testing perpetuates what critical scholars have

discussed and what I have termed assessment violence, whereby assessments ignore the learner's identity, agency, and lived experience. In contrast, a genuinely transformative STEM agenda must center the African learner as epistemically sovereign capable of producing, validating, and owning knowledge grounded in indigenous epistemologies. This sovereignty must be anchored in the triad of Conscience, Sovereignty, and Spirituality, foundational principles of the GPS–DALE Macrophage philosophy, which repositions education as an ethical, healing, and culturally responsive act of liberation. Therefore, the future of STEM in Africa lies not merely in what we build, but in whom we form through assessments anchored in culturally grounded frameworks such as the Zambian Modified Bloom's Taxonomy (Z-M BT). Reclaiming agency in STEM reform begins by investing in the learner's identity, imagination, and ideological clarity. Only then can educational systems evolve into authentic vehicles of transformation rather than remain barriers to realizing or achieving the Africa We Want.

Healing Pedagogy Declaration

We, educators, researchers, and curriculum thinkers, affirm that:

1. Assessment should not only measure but heal.
2. Our tools must be diagnostic, not extractive.
3. Our rubrics must reflect identity, not just productivity.
4. From Ubuntu, we learn that every learner is part of a greater cognitive community.
5. From Sankofa, we are reminded to recover what colonial systems told us to forget.
6. STEM reform must confront inherited trauma by restoring the African learner's sense of agency, dignity, and voice.
7. We must reject pedagogical violence.
8. We must uphold justice-driven curriculum transformation.
9. GPS-DALE Macrophage is our immunological response built to expose broken logic and nurture future-ready resilience.

This is our code. This is our Global Positioning Descriptive Analysis and Learning Evaluation.

Endnotes

This paper draws upon the Global Positioning Satellite–Descriptive Analysis and Learning Evaluation (GPS–DALE) Macrophage framework developed by the author. As an Immunological Compass for African Educational Renaissance, the GPS–DALE Macrophage is not merely an evaluation framework but a regenerative philosophy. Born from the urgency to rescue African education from technocratic decay, semantic overload, and colonial inertia, its strength lies in its capacity to sense, diagnose, heal, and rebuild the cognitive and moral fabric of learning systems.

- 1. Cognitive Immunity and Curriculum Healing:** Like a biological macrophage, the GPS–DALE Macrophage identifies toxicities within curricula such as assessment violence, curriculum misalignment, or performative reforms and targets them through a pedagogical immune response. It does not only flag what is wrong; but it activates a healing process rooted in cognitive heatmaps, diagnostic clusters, and threshold-predictive matrices. This elevates it beyond traditional tools and becomes an educational immune system.
- 2. Epistemic Sovereignty and Cultural Dignity:** Its core strength is its philosophical alignment with African epistemologies Ubuntu, Sankofa, and the ethic of communal regeneration. It reclaims the African learner not as a recipient of instruction, but as the regenerative core of transformation epistemically sovereign, spiritually grounded, and morally

awakened. This shift in locus from system to soul represents a new educational sovereignty for the Africa we want.

- 3. Supra-Diagnostic Precision:** Armed with over 1000 interrelated clusters and 370+ analytical variables, the GPS–DALE Macrophage surpasses linear evaluation. It detects policy gaps, skill imbalances, misaligned complexity levels, and mismatched learning intentions using tools such as multi-tier clustering, Agenda 2063 compliance flags, Skill–Policy–Ethics triangulation. No other tool currently integrates cognitive diagnostics, spiritual foundations, and policy monitoring with such precision.
- 4. Pan-African Unification and Agenda 2063 Alignment:** The GPS–DALE Macrophage holds continental potential as a unifying education reform architecture. By harmonizing Z-M Bloom’s Taxonomy, SDG4 indicators, and Agenda 2063 targets, it empowers Ministries of Education, ECAs, and continental bodies to monitor reforms with a common compass. In this way, it becomes Africa’s own evaluation engine, no longer dependent on foreign indices.

COMSTEDA as the Birthplace of the Macrophage Era

If recognized, COMSTEDA22/23 could mark the birthdate of the GPS–DALE Macrophage not as a single invention, but as the arrival of a new Pan-African consciousness in STEM reform. Like the release of an immune messenger into the bloodstream of African education, COMSTEDA provides the intellectual, symbolic, and continental stage for this unveiling.

This is not just about a model, but a movement but a continental shift from reactive reforms to regenerative transformation.

Notes on Key Terms

- 1. Semantically overloaded:** This refers to a phrase or theme carrying too many conceptual layers at once, thereby hindering clear analysis or execution.
- 2. GPS–DALE Macrophage:** The GPS–DALE Macrophage is an African-born, African-owned, and globally-relevant educational immune framework designed to detect, diagnose, and heal epistemic, cognitive, and policy gaps in formative and summative assessments across all learning levels. With over 1,000 diagnostic clusters and 370+ analytical variables, it offers Africa a unifying system for monitoring the implementation of all 7 Aspirations of Agenda 2063 and SDG4. It is our vision that COMSTEDA22 will be remembered as the historical platform that introduced this model to the world. From this moment, we seek continental partnerships (AU, NEPAD, ECAs), global education alliances (UNESCO, UNICEF, GPE), and academic networks to further validate, scale, and resource this model for integration in: (1) teacher training; (2) exam board reforms; (3) STEM innovation monitoring; and (4) regional quality assurance.
- 3. Pedagogical immune response:** A metaphor used in the GPS–DALE Macrophage model describing how educational systems identify, isolate, and correct harmful curriculum practices.
- 4. Regenerative core:** A GPS–DALE metaphor for the learner as the source of sustainable transformation within an educational ecosystem.
- 5. Ubuntu:** A Southern African ethic meaning, “I am because we are,” used to ground learning in dignity and interconnectedness.
- 6. Sankofa:** An Akan concept meaning “go back and fetch it,” encouraging the recovery of indigenous wisdom in curriculum reform.
- 7. Cognitive load theory:** A psychological theory proposed by John Sweller which examines how instructional design affects mental effort and learning retention.
- 8. DALE Matrix:** Descriptive Analysis and Learning Evaluation Matrix is a structured grid used to evaluate exam questions based on skills, complexity, and policy relevance.
- 9. Agenda 2063:** The African Union’s blueprint for a prosperous, integrated, and self-determined Africa, with education as a strategic pillar.

10. **SDG4:** Sustainable Development Goal 4 from the United Nations, focused on ensuring inclusive and equitable quality education.
11. **Diagnostic Clusters:** 18 zones within the GPS–DALE logic that evaluate exam quality, curriculum alignment, and learner impact.
12. **Cognitive heatmap:** A visual tool in the DALE Matrix that shows the intensity and imbalance of cognitive levels across an exam paper.
13. **Healing rubrics:** Rubric frameworks that prioritize cultural dignity, agency, and epistemic justice alongside content mastery.
14. **Africa learning ecosystem:** The interrelated environment of curriculum, pedagogy, and assessment that supports or hinders holistic learning.
15. **African epistemology:** Knowledge systems grounded in African philosophical traditions, emphasizing relationality, spirituality, and community reason.
16. **Semantic overload:** This refers to an excessive concentration of meaning within a phrase or sentence, overwhelming the reader’s cognitive processing capacity.
17. **Epistemological Specificity:** Refers to the precise identification and grounding of knowledge systems within their cultural, historical, and philosophical contexts. In contrast to general or imported epistemologies, epistemological specificity asserts that African education must be rooted in African ways of knowing. Within the GPS–DALE Macrophage framework, this principle ensures that learning is not only contextually relevant but also intellectually sovereign, allowing learners to reclaim and develop knowledge from their own ontologies and traditions.
18. **Performative:** This refers to actions or language that appear to drive change but lack substantive structural transformation or practical outcomes.
19. **Aesthetic Revisions:** This refers to editorial or design adjustments that enhance the visual appeal, formatting coherence, and reader-friendliness of the paper without altering its substantive content or conceptual argument. In the context of the GPS–DALE Macrophage framework, aesthetic revisions support regenerative clarity and dignified presentation, ensuring that form reflects and reinforces philosophical depth.
20. **Technocratic adjustments:** These are policy or structural changes focused primarily on systems, tools, or institutional mechanisms—often implemented without parallel shifts in ethical grounding, learner identity, or cultural logic. In GPS–DALE Macrophage diagnostics, such adjustments are critiqued when they prioritize operational reform over epistemic healing, resulting in performative rather than transformative impact.
21. **Ideological reorientation:** This is a shift in the foundational beliefs and values that shape education systems and reform agendas.
22. **Akan philosophy:** A West African philosophical system originating from the Akan people of Ghana and Côte d’Ivoire, emphasizing communal well-being, moral reciprocity, and ancestral wisdom. Key concepts such as Sankofa (“go back and fetch it”) are foundational to curriculum decolonization and cultural regeneration within the GPS–DALE Macrophage framework.
23. **Epistemic identity:** Refers to the learner’s self-concept as a knower shaped by cultural background, language, historical memory, and knowledge systems. Within the GPS–DALE Macrophage model, epistemic identity is essential for authentic learning and transformation, enabling learners to reclaim their intellectual agency and resist cognitive colonization.
24. **Risks being tokenistic:** This phrase signals the danger of symbolic inclusion without substantive change. In STEM reform, it refers to superficial gestures like naming themes or inserting African references without embedding indigenous logic, epistemic sovereignty, or learner-centered transformation. The GPS–DALE Macrophage cautions against such performativity that mimics reform while maintaining structural inequities.
25. **Ideologically neutral graduates:** Refers to learners who emerge from education systems without a clear philosophical, cultural, or ethical grounding often shaped by curricula that avoid political, historical, or spiritual positioning. In the GPS–DALE Macrophage model, this neutrality is seen not as objectivity but as erasure disconnecting learners from their identity, context, and transformative potential.
26. **International Coding Academy:** A generic label used to describe private or donor-funded institutions offering coding and digital skills programs across African countries. While such academies may enhance employability, the GPS–DALE Macrophage cautions that without cultural rooting and epistemic alignment, they risk exporting external logics rather than nurturing sovereign, locally-grounded innovation.

27. **Andela:** A talent accelerator originally launched in Nigeria to train software developers for global tech markets. While praised for scaling digital skills, Andela has also been critiqued for prioritizing outsourcing pipelines over local innovation ecosystems. Within the GPS–DALE Macrophage lens, such models must be examined for their long-term contribution to epistemic sovereignty and continental development.
28. **Cultural revalorization:** The process of restoring dignity, legitimacy, and centrality to indigenous cultures, philosophies, and knowledge systems in education. Under the GPS–DALE Macrophage, cultural revalorization is not nostalgic recovery, but a regenerative act that affirms the African learner’s epistemic worth and positions local wisdom at the heart of STEM reform.
29. **Indigenous leadership Archetypes:** Models of leadership drawn from African traditions, stories, and social structures—often emphasizing wisdom, interdependence, spiritual authority, and moral stewardship. Unlike technocratic leadership models, these archetypes prioritize communal flourishing and ethical foresight. In the GPS–DALE Macrophage, they inspire learner formation and educational leadership rooted in ancestral logic.
30. **African cosmologies:** This refers to the diverse traditional understandings and worldviews held by many African cultures about the nature of the universe, the relationship between humans and the divine, and the interconnectedness of all life. These cosmologies are foundational in shaping African spiritual beliefs, ethics, social organization, and rituals.

Worldviews and ontologies rooted in African traditions that emphasize the interconnectedness of the spiritual, natural, and human realms. They offer holistic understandings of existence, time, knowledge, and purpose. In the GPS–DALE Macrophage model, African cosmologies guide pedagogical healing, situate the learner within a larger ethical universe, and counter reductionist STEM paradigms.
31. **Pedagogical identity:** This refers to the way teachers or educators understand, construct, and express their sense of self in relation to their teaching practice. It encompasses their beliefs, values, knowledge, skills, and attitudes about teaching and learning, as well as how they see their role and purpose within the educational context.

The educator’s internalized framework of beliefs, values, and practices that shapes how they teach and relate to learners. It includes their epistemological stance, cultural orientation, and ethical posture. In the GPS–DALE Macrophage, pedagogical identity must be healed and re-rooted to disrupt colonial instructional habits and foster transformative, learner-centered STEM education.
32. **Pan-African consciousness:** This refers to a collective awareness and sense of identity among African people and the African diaspora, emphasizing unity, solidarity, and shared heritage across the continent and beyond. It is a political, cultural, and social mindset that seeks to affirm African identity, promote self-determination, and challenge colonial and neocolonial legacies.

A political, cultural, and educational awareness that affirms the unity, agency, and shared destiny of African peoples across the continent and the diaspora. It calls for educational models that resist fragmentation, decolonize knowledge, and build continental solidarity. The GPS–DALE Macrophage elevates Pan-African consciousness as a critical learning outcome—shaping learners who think, innovate, and lead with Africa in mind.
33. **Assessment violence:** This refers to testing approaches that harm learners by ignoring their cultural identity and agency. The concept is influenced by scholars such as Paulo Freire (1970), Linda Tuhiwai Smith (1999), and Antonia Darder (2012), who argue that such practices perpetuate epistemic injustice and reinforce colonial hierarchies in education. The structural and psychological harm inflicted by evaluation practices that disregard learner context, identity, or developmental readiness. This includes over-testing, rote recall emphasis, cultural erasure, and exclusionary formats. In the GPS–DALE Macrophage model, assessment violence is treated as a “curriculum toxin” that must be neutralized through healing rubrics, diagnostic alignment, and epistemic justice.
34. **Critical Thinkers:** The term assessment violence draws on critical pedagogical insights from Paulo Freire’s critique of the “banking model” of education (1970), which dehumanizes learners by treating them as passive recipients of knowledge. Gloria Ladson-Billings (1995) extends this by framing educational disparity as “educational debt,” rooted in systemic racism rather than mere achievement gaps. Linda Tuhiwai Smith (1999) explores how assessments can perpetuate colonial harm when stripped of Indigenous epistemologies. Antonia Darder (2012) critiques how classroom power dynamics marginalize cultural identity through standardised evaluations. Njoki Wane (2008), working within African Indigenous knowledge systems, warns that ignoring spiritual, communal, and ancestral dimensions in assessment frameworks amounts to epistemic erasure. Together, these scholars argue that assessments which fail to respect epistemic identity

and contextual reality inflict violence on the African learner and obstruct emancipatory education. Freire, Paulo. *Pedagogy of the Oppressed* (30th Anniversary Ed.). New York: Continuum, 2000. Originally published in 1970, this work advocates for the critical formation of consciousness (conscientização) as the core of liberatory education.

35. Conscience, Sovereignty, Spirituality: Core values in the GPS–DALE Macrophage model representing the moral and identity-based dimensions of learning. Three of the eight foundational pillars of the GPS–DALE Macrophage framework. Conscience refers to the learner’s moral compass and capacity for ethical judgment. Sovereignty asserts the learner’s right to epistemic independence and cultural authorship. Spirituality grounds learning in purpose, transcendence, and ancestral wisdom. Together, these pillars move STEM education beyond technical skills toward holistic, soul-rooted transformation.

36. Curriculum toxins: Refers to harmful content, pedagogy, or colonial frameworks embedded in curricula, often invisible without critical diagnostics.

Harmful elements embedded in educational content, pedagogy, or structure that impair learner growth, identity, or agency. These include colonial narratives, Eurocentric bias, misaligned objectives, and rigid assessment forms. Within the GPS–DALE Macrophage model, curriculum toxins are detected through diagnostic clusters and neutralized through regenerative design, cultural revalorization, and epistemic healing.

37. Epistemic sovereignty: The learner’s capacity to generate, validate, and own knowledge from within their cultural and intellectual heritage.

The learner’s capacity to generate, validate, and own knowledge rooted in their cultural, linguistic, and intellectual heritage. It affirms the right to think, teach, and learn from African worldviews without dependency on imported paradigms. Within the GPS–DALE Macrophage, epistemic sovereignty is central to forming regenerative learners capable of leading Africa’s transformation with dignity and authenticity.

38. Zambian Modified Bloom’s Taxonomy: The Z–M BT grid is an original adaptation of Bloom’s Taxonomy, developed by the author to meet the specific diagnostic needs of Zambian STEM assessment under the DALE Matrix.

A localized adaptation of Bloom’s Taxonomy, developed by the author to better evaluate cognitive depth in Zambian STEM assessment contexts. It reorders and renames cognitive levels as: (1) Recall and Recognition; (2) Interpret and Explain; (3) Apply Practically; (4) Judge and Decide; (5) Problem-Solve and Differentiate; (6) Innovate and Design Solutions.

The Z–M BT supports the DALE Matrix in mapping question difficulty, skill complexity, and policy relevance, offering a culturally responsive diagnostic framework.

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