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Beyond the Score: Rethinking TIMSS Underperformance in Participating African Countries through Open Education, Universal Design for Learning, and Self-Directed Learning

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Abstract. The African countries that participated in the 2023 Trends in International Mathematics and Science Study (TIMSS) did not perform well. The paper discusses systemic challenges, including language barriers, resource limitations and infrastructural deficits that lead to underperformance. This paper discusses the potential of Open Educational Resources (OERs) and Open Educational Practices (OEPs) in addressing these issues by creating inclusive and self-directed learning environments. This paper uses TIMSS reports and existing literature to explore the ways in which Open Educational Resources (OER), Universal Design of Learning (UDL), and Self-Directed Learning (SDL) may offer alternative ways of interpreting and responding to underperformance in STEM education. It does this by using a qualitative conceptual-analytical method that is informed by insights from an integrative literature. The analysis shows that in the African context, TIMSS scores are not only an indicator of the learners' ability but also of the bigger issues of unequal access to learning facilities, low inclusivity in the design process of learning and limited opportunities for learner autonomy. The research, viewed through the lens of OER and open pedagogical practices, suggests resource availability, content localisation, and collaborative learning techniques can be used to reform STEM learning experiences and advocates for an educational framework that uses openness to promote equity, engagement, and academic achievement in Africa. As a conceptual review, the analysis relies solely on secondary evidence and does not empirically validate the suggested framework.

Keywords: TIMSS; Open Educational Resources; Open Educational Practices; Self-directed learning; Universal Design for Learning; STEM Equity

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1. Introduction

The Trends in International Mathematics and Science Study (TIMSS) shows that participating African nations continue to perform poorly, which highlights the growing gaps in STEM learning outcomes worldwide and the unequal ability of educational institutions to engage in a knowledge economy that is gradually becoming more globalised. As international large-scale assessments increasingly influence global policy narratives, curriculum reforms, and funding priorities, Africa's marginal position in these comparative metrics raises critical inquiry about the systemic, pedagogical, and infrastructural elements that affect learners' engagement with mathematics and science.

Recent studies associate these outcomes with resource constraints, linguistic variations between native languages and the medium of instruction, insufficient teacher professional development, and limited access to high-quality educational materials (Ayanwale et al., 2023; Elouafi et al., 2025). In numerous contexts, classroom instruction predominantly remains teacher-centred, with minimal implementation of inquiry-based, technology-enhanced, or participatory methodologies, widening the disparity between the experiences of African learners and the competencies assessed by global STEM standards (Eltaiba et al., 2025; Panakaje et al., 2024).

Poor performance in TIMSS has been identified in participating African countries and has been attributed to poor access to educational resources (Mokgwathi et al., 2025). In TIMSS 2023, the African participants were Côte d'Ivoire, Morocco, and South Africa. Although this is still a very important aspect, the current analysis indicates that access is not enough to explain the performance gaps. As an Open Educational approach, the presence of resources should be supplemented with pedagogical activities that facilitate substantial interaction. Based on the UDL, learning contexts might not sufficiently support learner variability, especially in situations typified by linguistic diversity, disparate background knowledge, and socio-economic limitations (Espada-Chavarria et al., 2023). Lack of a flexible approach to content representation and expression of learners can thus be a factor in continued performance gaps, which means that the problem of poor TIMSS results is not just an access problem, but also a design and inclusivity issue (Muskens et al., 2024).

Although open education, encompassing OER and OEP, has received international attention for enhancing access, democratising knowledge, and fostering equitable learning pathways, its capacity to reduce the persistent pedagogical challenges shown in TIMSS performance is still inadequately examined in African contexts (Díaz-Suárez et al., 2025; Tlili et al., 2023). Beyond reducing the cost of materials, OER allow STEM information to be localised, translated, and culturally contextualised, assisting in the alignment of learning materials with the language and sociocultural reality of learners (Olivier & Olivier, 2022; Letsoalo, 2024). The OEP enhances collaborative knowledge generation, inquiry-based learning, and reflective problem-solving, which strongly align with the cognitive domains assessed in TIMSS: knowing, applying, and reasoning (Gavrilas & Kotsis, 2025; Martin et al., 2020).

OER, OEP, technology-enhanced learning, and open pedagogies are still not consistently included in STEM classrooms in Africa, despite their potential. Opportunities to augment feedback literacy, facilitate SDL, or improve conceptual comprehension using adaptive technology, are unexplored. African STEM curriculums still do not extensively use AI-supported tutoring systems, intelligent feedback tools, and personalised learning platforms, which are already standard components of educational innovation globally (Gligorea et al., 2023; Younas et al., 2025). This mismatch between the higher-order abilities that are highlighted in international examinations, classroom practice, and curriculum goals leads to persistent performance gaps (Bofah & Hannula, 2015; Kanjee et al., 2024).

Infrastructure deficiencies, capacity limitations, and a lack of pedagogical innovation are some of the major obstacles that Africa still faces in enhancing STEM education (Amegah et al., 2023; Chisom et al., 2024). The need for more transformational and culturally relevant educational approaches is indicated by the sluggish rate of growth, even while TIMSS offers internationally comparable, policy-relevant data to enable system-wide change (Mullis et al., 2020). This study argues that OER and OEP, along with UDL, SDL and technology-enhanced formative assessment, offer complementary perspectives for understanding and addressing TIMSS underperformance in participating African countries.

OER and OEP promote equal access to localised, high-quality learning resources and participatory pedagogies. UDL promotes inclusive learning design responsive to learner diversity. SDL promotes learner agency and self-regulation. Technology-enhanced formative assessment promotes timely feedback and individualised instruction. Together, these approaches offer a conceptual framework for considering how structural, curricular, and pedagogical barriers may be addressed to support more equitable STEM learning. The paper presents a conceptual model that situates open education within the broader context of globalisation and transnational knowledge exchange, illustrating how openness and technology may reduce structural inequalities and enhance the relationship between STEM learning practices and the competencies required by TIMSS and global scientific literacy.

1.1 Research Questions

The main research question answered in this study is:

How do OER, OEP, UDL, and SDL conceptually address the barriers associated with TIMSS underperformance in participating African countries?

The following sub-questions guided this study:

1. How can Open Education, through OER and OEP, together with UDL and SDL, contribute to addressing TIMSS underperformance in participating African countries?
2. What structural, curricular, and pedagogical factors contribute to TIMSS underperformance in participating African countries beyond measured achievement scores?
3. What are the implications of this conceptual framework for promoting equitable and inclusive STEM learning in participating African countries?

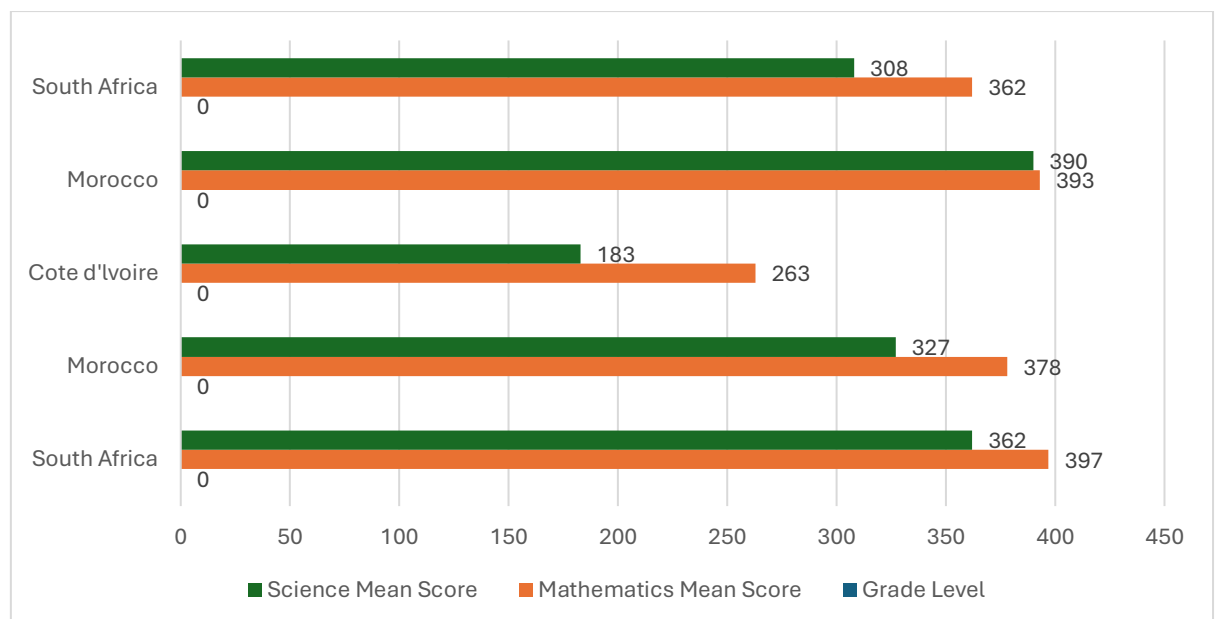
2. Literature Review

2.1. STEM education as a global priority

Globally, the demand for creative STEM professionals is rising, and is essential for national growth (Kayan-Fadlelmula et al., 2022). STEM integrates science theory with practice, fostering critical thinking, creativity, and problem-solving skills needed to tackle global issues like climate change (Sari et al., 2024). Despite STEM's central impact in economic development, evidence from international assessment literature suggests that student performance in STEM has been stagnated over the past decade (Alsayer, 2025), with a noted workforce shortfall (Pongsophon, 2023). STEM education is crucial for preparing future generations for a tech-driven world. TIMSS, an international assessment from IEA, evaluates fourth and eighth graders' math and science proficiency every four years since 1995 (Martin et al., 2016), offering data on global student performance trends (Martin et al., 2020). It aims to assess students' math and science skills, considering curricular and contextual educational factors (Strietholt et al., 2025), enabling comparisons of global performance variability (von Davier et al., 2024).

2.2. TIMSS Performance in Africa

TIMSS International Benchmarks evaluate student skills in mathematics and science at four levels: Advanced (625), High (550), Intermediate (475), and Low (400) (von Davier et al., 2024). Against this framework, the three participating African countries all performed below the low benchmark of 400, with eighth-grade science scores of 362 for South Africa, 327 for Morocco, and 183 for Côte d'Ivoire. In mathematics, the scores were 397 for South Africa, 378 for Morocco, and 263 for Côte d'Ivoire (von Davier et al., 2024). Morocco scored 390 in fourth-grade science, compared to South Africa's 308, while in mathematics Morocco scored 393 and South Africa recorded 362.



Source : von Davier et al., 2024

Figure 1: TIMSS 2023 Mathematics and Science Scores for Participating African Countries

Ayanwale et al. (2023) observe that South African learners demonstrated suboptimal performance, even when assessed against significantly younger students; the assessment occurred at the fifth and ninth grades instead of the fourth and eighth grades. Elouafi et al. (2025) have identified a variety of contributory factors to the unsatisfactory performance of Moroccan students in the TIMSS 2019 mathematics assessment, including income disparity, deficient educational infrastructure, overcrowded classrooms, and a lack of qualified teaching personnel. These challenges are exacerbated by language barriers, reduced student engagement, and the lack of dynamic teaching strategies (Xiao et al., 2024). Often, professional development opportunities for educators are limited in areas like formative assessment and differentiated instruction (Yuen et al., 2023). Students also have to contend with limited access to important resources such as libraries and electronic devices, and experience challenges in managing the classroom (Gibbs, 2023).

Chikoko and Mthembu (2020) noted that South Africa has huge economic disparities that lead to unequal educational opportunities. Specifically, African learners tend to be lower achievers in mathematics. The medium of instruction is significant when considering education as the dominant language that learners use to communicate and share ideas (Sibanda & Tshehla, 2025). Language is a critical factor in the gaining of knowledge and the exchange of concepts within educational contexts. Students from economically disadvantaged backgrounds typically begin their schooling in a new language such as English in the fourth grade. This complicates their understanding of complicated ideas in a second language, which influences academic performance in South Africa (Kanjee et al., 2024). Nyamunda (2025) identifies instructional time, student-teacher ratios, and linguistic diversity as crucial factors determining academic success.

In Côte d'Ivoire, rural poverty hampers educational performance due to challenges such as low enrolment, teenage pregnancies, gender inequities and inadequate facilities (Celik, 2024). The main reasons behind poor performance in TIMSS 2023 among the three participating countries were language barriers, lack of access to learning resources and infrastructural deficits. To address these challenges, Elouafi et al. (2025) suggest a comprehensive strategy that involves enhancing resources, providing targeted support, and implementing effective instructional methodologies to better support students and teachers. Establishing an inclusive and equitable educational ecosystem demands that all students have access to qualified teaching professionals, innovative pedagogical strategies, and sufficient resources (Chisom et al., 2024).

2.3 Conceptual Framework

This study proposes a mediated model that links contextual structural barriers to TIMSS outcomes through a set of interventions and mechanisms.

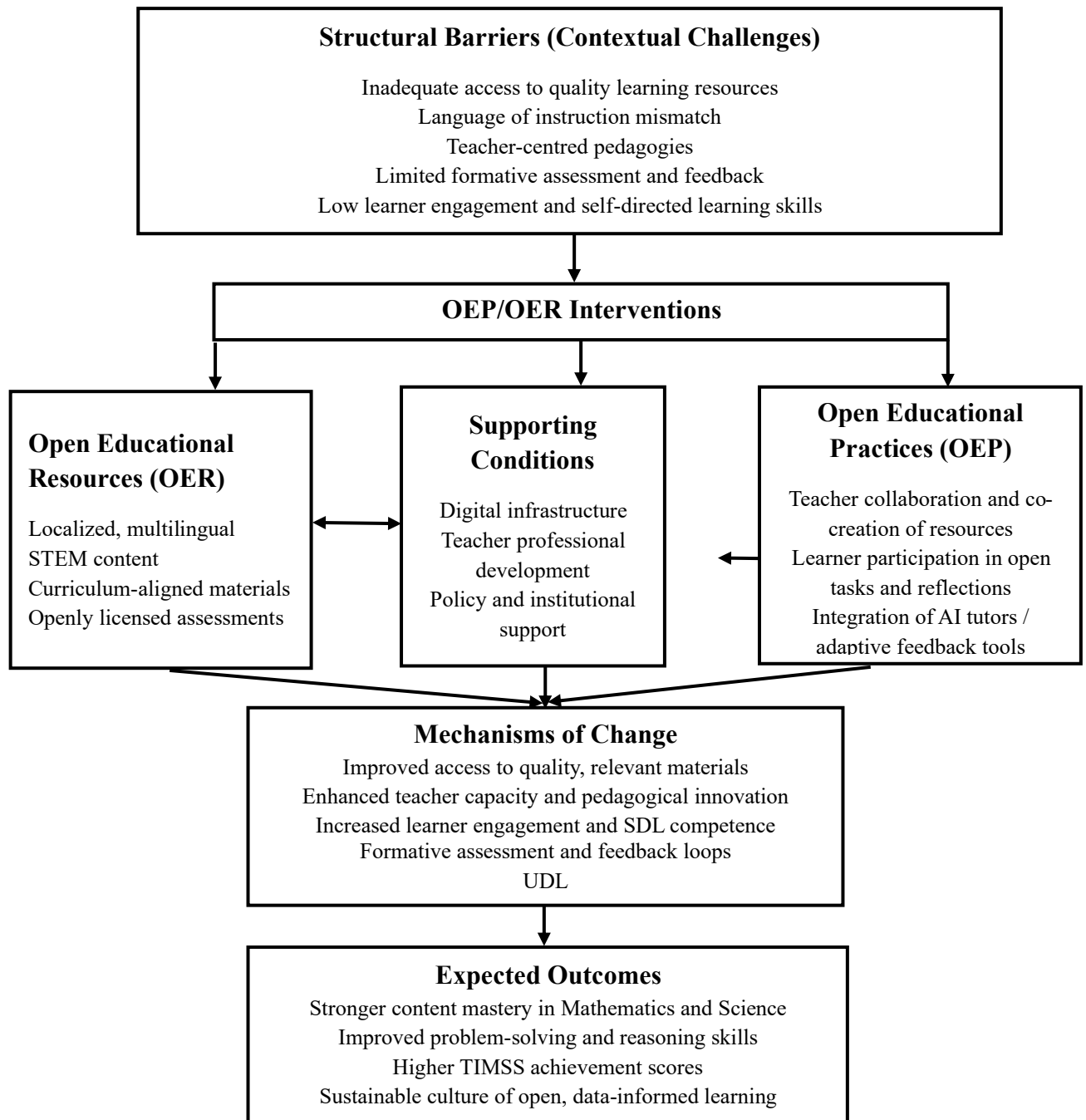


Figure 2: Conceptual Framework Linking OER/OEP Mechanisms to TIMSS

The framework suggests that the TIMSS-related underperformance of participating African countries is a function of the interaction of structural and pedagogical conditions. Open and inclusive learning approaches, such as OER/OEP, UDL, SDL, and AI-supported feedback systems, are envisioned as design features that may help to overcome these barriers through enhanced access, learner engagement, conceptual understanding, and self-regulation.

2.4. Mechanisms of Change

OER and OEP offer complementary mechanisms for addressing barriers to STEM learning in participating African countries. OER mainly increase educational access by allowing teachers to retain, reuse, revise, remix, redistribute, translate, and adapt openly licensed STEM resources to local contexts (Van Allen & Katz, 2023; Arispe et al., 2025; LeMire, 2025). Conversely, OEP focus on teaching and learning processes by encouraging collaborative, inquiry-based and learner-centred pedagogies that foster active participation and knowledge co-construction (Mhlongo et al., 2023). OER and OEP together take the focus from access to meaningful engagement with learning.

These complementary mechanisms within the TIMSS framework give a conceptual roadmap to tackle some barriers identified in the literature. OER address the challenges of resource constraints and linguistic barriers through the adaptation and localisation of STEM learning resources. OEP promote pedagogical practices that improve inquiry, problem-solving and learner engagement, which are the competencies that the TIMSS cognitive domains reflect, that is, knowing, applying and reasoning (Gavrilas & Kotsis, 2025; Regmi & Jones, 2020). Studies further suggest that such approaches may improve the relevance and accessibility of STEM instruction, thereby increasing learner engagement and teacher capacity in resource-constrained settings (Abusamra et al., 2025; Borda et al., 2020; Levy-Feldman, 2025; Pellegrino, 2024; Yassin & Jung, 2021). But their effectiveness depends on context, including teacher readiness, the quality of resources, infrastructure and institutional support.

2.4.1. OER Initiatives in Africa and their relevance to TIMSS

Several Open Educational Resource (OER) initiatives across Africa show how open education can tackle barriers commonly related to STEM learning such as limited access to quality educational resources, language diversity, teacher capacity and the contextual relevance of instructional materials. These initiatives were not intended to improve TIMSS performance, but they do illustrate practical mechanisms by which open educational approaches can contribute to more inclusive and equitable STEM learning environments.

One of the pioneering initiatives is the Teacher Education in Sub-Saharan Africa (TESSA), which provides freely licensed activity-based learning resources to support teacher professional development and learner-centred STEM instruction (Mokgwathi, 2025). TESSA promotes inquiry-based learning and problem solving, which are consistent with the cognitive processes assessed by TIMSS and helps teachers to foster deeper conceptual understanding (Gardner et al., 2018). Similarly, ACE Maths, coordinated by the South African Institute for Distance Education (SAIDE) with partner institutions across Africa, provides openly

licensed mathematics resources for teacher education. ACE Maths builds teacher capacity and promotes pedagogical practices that can support meaningful mathematics learning across various educational contexts (Africa, 2022; Kumm & Graven, 2024) through the use of problem-oriented approaches to mathematics instruction.

Localisation and collaborative knowledge sharing are highlighted by other initiatives. The African Storybook Initiative offers multilingual, culturally relevant storybooks that embed numeracy in familiar contexts, thus helping to overcome language-related barriers to mathematics learning (Stranger-Johannessen, 2017). Similarly, OER Africa provides curriculum adaptation, collaborative resource development, teacher networks and open repositories that facilitate localisation of instructional materials and sharing of best practices in teaching (Mitchell et al., 2024). Collectively, these initiatives illustrate how OER can support educational access, contextualisation and teacher development mechanisms that complement the wider conceptual framework proposed in this paper for understanding and addressing barriers associated with TIMSS underperformance in participating African countries.

2.4.2. Localisation of OER for STEM Instruction

In many African contexts, mismatched curriculum and language challenges continue to be major causes of worse TIMSS performance. Translation, adaptation, and contextualisation of STEM information are made possible by OER and OEP, which offer a potent localisation mechanism that immediately eliminates these limitations (Letsoalo, 2024). Promising strategies for fostering educational inclusivity, collaboration, and localised knowledge generation are OER and OEP.

Open Educational Resources (OERs) offer the benefit of adaptability and customisation to align with a particular educational context's specific language and content needs (Olivier & Olivier, 2022). OEP also enhances inquiry through mechanisms of collaborative knowledge construction, open discourse, and the co-development of educational tasks (Brandenburger, 2022). According to UNESCO (2019), OERs are resources for learning, teaching, and research available in various formats and media, either in the public domain or copyrighted and distributed under specific licenses that permit unrestricted access, reuse, modification, and redistribution by third parties.

By empowering learners to contribute to content creation, remix OER, or co-design learning trajectories, OER nurture both agency and ownership, which are pivotal for sustained engagement and the cultivation of higher-order cognitive skills (Ndiangu et al., 2025). Coetser et al. (2022) suggested that translating key concepts, especially discipline-specific terminology, into glossaries serves as a method to address the language barrier. OERs promote the development and improvement of educational materials, offering benefits to educators and higher education institutions. They enable the translation of information into local languages, adaptation to local contexts, and provision of relevant examples in evaluating the challenges related to access to educational resources. The rise of new technologies has heightened the significance of ensuring access to education

and resources (Ogange & Carr, 2021). This is particularly significant in SDL, enabling students to choose their resources. OERs are significant in realising such resources (Olivier & Olivier, 2022). The foregoing discussion highlights the need to explore how open educational approaches might address persistent gaps in STEM learning outcomes. The localisation of OER thus constitutes a complementary mechanism in the proposed framework to address TIMSS-related challenges of resource relevance, language diversity and learner engagement. However, for localisation to be successful, attention needs to be paid to the quality of translation, teacher capacity, cultural appropriateness and sustainable processes for resource development and maintenance.

2.4.3. Universal Design for Learning (UDL)

UDL offers a conceptual lens for analysing learners' access to educational resources as well as whether teaching and learning environments are purposefully created to meet a range of cognitive, linguistic, cultural, and socioeconomic needs in the context of large-scale assessments like TIMSS (Asula-Abaver & Machaba, 2026). The combination of UDL and OEP moves from a focus on access to inclusive participation by highlighting the significance of designing learning environments that enable all learners to engage meaningfully with STEM content (Sewell et al., 2022). UDL, developed by CAST, is grounded in three key principles: multiple means of engagement, representation, and action and expression to proactively respond to learner variability through flexible instructional design (McKenzie & Dalton, 2020; Orndorf et al., 2022).

Within the framework of participating African countries, UDL provides a conceptual mechanism for tackling several barriers related to TIMSS underperformance, including linguistic diversity, disparities in learning opportunities, variation in learners' prior knowledge, and underutilisation of inclusive instructional practices. UDL adds value to OER and OEP by promoting flexible curriculum design and learner-responsive pedagogies, so that increased access to educational resources is matched by inclusive opportunities for participation and learning. But its effectiveness depends on how it is used in context, on the capacity of teachers and on institutional support. Therefore, its potential contribution to improving STEM learning is reported in this paper as a conceptual proposition to study empirically in the future, and not as a causal relationship.

2.4.4. Inquiry-based and interactive learning mechanism

Inquiry-based learning (IBL) is key to STEM education, emphasizing reasoning, experimentation, and evidence-based investigation (Morris, 2019; Twizeyimana et al., 2024). OER and OEP facilitate inquiry-based STEM learning, even with limited resources, by providing access to interactive activities through open simulations, virtual labs, manipulatives, and multimedia (Kefalis et al., 2025). Inquiry-based and interactive learning approaches align closely with the cognitive demands of TIMSS, which emphasise scientific reasoning, exploration, hypothesis testing, and application (Gillies, 2023). OER and OEP amplify inquiry and engagement by providing open-ended tasks, interactive simulations, and collaborative platforms that stimulate deep thinking (Kunnath & Botes, 2025). Inquiry-driven learning supports STEM motivation, develops scientific curiosity,

and fosters engagement, key drivers of long-term conceptual retention (Sundari & Utami, 2024). Research shows that inquiry-based science education enhances learners' motivation and capacity to engage critically with scientific ideas (Chang et al., 2016; Teplá & Distler, 2025). OER expands inquiry opportunities by offering openly licensed experiments, virtual labs, real-world datasets, and interactive activities that allow learners to explore STEM concepts in dynamic ways (van Riesen et al., 2018).

Inquiry-based learning assumes a critical role in the TIMSS, as the assessment requires students to go beyond simple knowledge recall and apply their comprehension in novel contexts (Antonio & Prudente, 2024; Mamombe et al., 2020). In STEM education, OEP advances inquiry-based learning, promotes reflective practices, and broadens the scope for formative assessments (Ješková et al., 2022). Engagement with open tasks, the remixing of open content, or participation in open assessments stimulates learners to engage in advanced metacognitive processes, thus reinforcing understanding and resilience (Brown et al., 2024).

Importantly, OEP creates educational settings conducive to multilingual STEM instruction, which is a critical factor in African contexts where linguistic diversity poses considerable pedagogical challenges (Mrosso et al., 2025). One instructional technique that encourages learning motivation is inquiry-based learning (Sundari & Utami, 2024). Scientific curiosity and learning motivation are enhanced by the inquiry-based learning approach (Chang et al., 2016). One approach to teaching science that allows pupils to explore a topic that simulates scientific inquiry is called inquiry learning (Dmoshinskaia et al., 2021).

Since future learning usually builds upon prior information, active learning strategies like inquiry-based learning are essential to achieving deep understandings in science education (van Riesen et al., 2018). Inquiry-Based Science Education (IBSE) positively influences junior high school students' motivational attitudes towards STEM subjects, fostering interest and maintaining positive attitudes towards natural sciences (Teplá & Distler, 2025). Inquiry-based learning is considered to be one of the pedagogical levers by which OER and OEP may help overcome TIMSS-related barriers by boosting learner engagement, scientific reasoning, and higher-order thinking. However, its effectiveness is likely to depend on enabling conditions such as teacher capacity, availability of appropriate learning resources and supportive classroom environments.

2.4.5. SDL and feedback mechanism

SDL provides an important conceptual lens through which to understand how learners develop the autonomy, metacognitive skills, and self-regulation necessary to engage successfully with STEM learning. SDL is a process in which learners undertake the responsibility, with or without assistance from others, for diagnosing their learning needs, formulating learning goals, identifying human and material resources for learning, selecting and implementing appropriate learning strategies, and evaluating the outcomes of learning (Knowles, 1975). These competencies are particularly important in STEM education, as they equip

learners to solve problems, think critically, and adapt to increasingly complex learning environments (Kemp et al., 2024). OER promote SDL by providing access to a larger number of learning resources that can be adjusted to the specific needs of the learners. OEP encourages reflection, cooperation and active involvement in the learning process (Horn et al., 2018; Van den Berg & Du Toit-Brits, 2023).

Feedback is a key factor in improving SDL, as it allows learners to monitor their progress, identify gaps in knowledge and regulate subsequent learning activities (Hattie, 2013). Formative assessment, self-assessment and reflection enable learners to develop their awareness of their strengths and areas for improvement so that they can make informed decisions about their learning strategies (Panadero et al., 2016; Yan & Carless, 2022). Open assessment practices also facilitate this process, as they enable educators and learners to develop, adapt and employ assessment resources that are openly available, and that meet a variety of learning needs (Chiappe et al., 2016).

Within the TIMSS context, SDL and formative feedback offer a conceptual mechanism to overcome the barriers of learner agency, limited formative assessment, and passive learning. SDL encourages the development of self-regulation, reflective learning and strategic use of feedback to facilitate the learners' development of higher order thinking and problem-solving competence that are reflected in the cognitive domains of applying and reasoning in TIMSS. SDL thus complements OER, OEP and UDL by improving the ability of learners to actively and independently engage with STEM learning.

2.4.6 Technology and AI mechanism

The integration of artificial intelligence (AI) tutors and adaptive learning systems into OEP could offer more personalised learning experiences through tailored instruction, strategic scaffolding, and timely formative feedback (Gligorea et al., 2023). These technologies can be used to align instructional content to learners' needs, diagnose misconceptions and guide subsequent instructional decisions, thus supporting the development of competencies often measured in international assessments like TIMSS, such as complex problem solving and analytical reasoning (Gayed, 2025; Younas et al., 2025). But the effectiveness of AI-supported learning depends on how it is implemented pedagogically and should be viewed as complementary, not a substitute for teacher expertise and instructional decision-making.

2.4.7 Adaptive Learning

Adaptive learning builds on Open Education, UDL and SDL by offering personalised learning experiences that adapt to individual learners' needs, prior knowledge and learning progress. Unlike traditional instructional practices that generally follow a one-size-fits-all teaching approach, adaptive learning technologies, which utilise data on learner performance, provide differentiated content, personalised feedback, and targeted learning routes (Villegas-Ch et al., 2025). An example of this approach is intelligent tutoring systems (ITS), which use advances in artificial intelligence to analyse the performance of learners in real time and to recommend instructional support that responds to the individual needs of learners (Peng & Spector, 2019; Spitzer & Moeller, 2023).

Within the framework of TIMSS, adaptive learning offers a conceptual mechanism for managing learner variability and supporting development of mathematical and scientific reasoning. Technology-enhanced learning and assessment environments can provide timely feedback, track learners' progress, and customise learning experiences in ways that promote self-regulation and continuous growth (Ercikan & Pellegrino, 2017; Pellegrino, 2024). SDL is also facilitated by these technologies as they allow learners to set goals, track their understanding and modify their learning strategies over time (Kruger, 2020). However, the effective deployment of adaptive learning requires considerations such as digital infrastructure, teacher capacity, fair access to technology and the ethical use of learner data. Thus, adaptive learning is presented as a supplementary mechanism in the proposed conceptual framework and not as a single solution to TIMSS underperformance.

2.4.8 AI Tutors

Standardised instruction is often used in traditional classrooms, but it may not be able to adapt to differences in students' prior knowledge, learning pace, and academic needs (Holmes et al., 2019). STEM education involves complex ideas and problem-solving, and limited opportunities for individualised guidance and timely feedback can contribute to persistent learning gaps (Al Nabhani et al., 2025). One emerging approach to complement existing pedagogical practices is through the use of AI-supported tutoring systems, which provide personalised explanations, feedback, and learning support based on learner interactions (Hwang et al., 2020; Lee & Kwon, 2024).

The proposed conceptual framework indicates that AI tutors could be a possible mechanism to overcome the barriers of individualised support, availability of feedback and learner engagement in STEM learning. AI-based systems can support learners in developing conceptual understanding, problem-solving skills, and self-regulated learning practices through the analysis of learner responses and the provision of adaptive instructional support (Kim & Kim, 2022; Zhai & Krajcik, 2025). AI tutors can also complement teacher practices by supporting assessment, identifying learning difficulties, and enabling educators to provide more targeted guidance, rather than replacing the teacher's role (Van et al., 2021). The educational value of AI tutors, however, is contingent on equal access to digital infrastructure, teacher preparedness, responsible use of learner data, and attention to potential algorithmic biases.

3. Methodology

This paper adopts a conceptual-analytical approach, informed by an integrative review of the literature, to examine TIMSS underperformance in participating African countries beyond traditional score-based interpretations. Instead of producing new empirical data, the study brings together evidence from official TIMSS reports and peer-reviewed literature on Open Education, UDL, and SDL to create a theoretically grounded framework for making sense of STEM learning outcomes. Conceptual research is suitable for synthesising existing knowledge, combining different theoretical perspectives and generating new conceptual insights that go beyond descriptive analyses (Jaakkola, 2020). Thus, the literature

was purposefully selected for its relevance to TIMSS performance, STEM education, Open Education, OER, UDL, and SDL in African educational contexts. Sources were included if they offered conceptual, theoretical, or empirical insights that informed the interpretation of TIMSS underperformance or the application of Open Education, UDL, and SDL to STEM education. Priority was given to peer-reviewed journal articles, academic books, and official TIMSS reports that advanced the conceptual development of the study.

An iterative reading and conceptual synthesis of the selected literature was performed. We linked evidence from TIMSS reports to findings from the broader literature to explore recurring concepts, patterns, areas of convergence and divergence, and explanatory relationships concerning educational access, curriculum, pedagogy, learner support, and educational equity. These recurring themes were then interpreted through the complementary lenses of Open Education, UDL, and SDL to develop an integrated conceptual framework for understanding factors that may influence STEM achievement in participating African countries. Being a conceptual paper, it does not attempt to establish causal relationships or empirically validate the proposed framework. Rather, it provides a theoretically based explanation for the underachievement of TIMSS and develops an integrated conceptual framework that can inform future empirical research, educational policy, curriculum development and practice.

4. Discussion

Research Question One:

How can Open Education, through OER and OEP, together with UDL and SDL, contribute to addressing TIMSS underperformance in participating African countries?

The synthesised literature in this study suggests that Open Education through OER and OEP, in combination with UDL and SDL, offers a complementary conceptual framework for rethinking TIMSS underperformance beyond achievement scores. The reviewed literature unanimously attributes poor performance to the effects of structural inequalities, limited access to quality learning resources, insufficiently inclusive instructional practices and constrained learner agency rather than to the abilities of learners alone. In this sense, low performance on TIMSS is not only a deficit of the learner but also indicative of wider educational conditions that shape opportunities to learn STEM.

The literature also notes that OER and OEP help address these challenges by expanding equal access to high-quality STEM learning resources and allowing educators to adapt, localise and contextualise content to the linguistic, cultural and curricular contexts of learners. By linking abstract concepts to the lived experiences of the learners, localised OER bring more relevance to STEM instruction, while OEP enable collaborative, inquiry-based and participatory pedagogies that foster active construction of knowledge rather than passive reception. Collectively, these approaches move the focus of Open Education from access to meaningful engagement and conceptual understanding. The findings of Romero-Ariza et al. (2025), which link the use of OER to more active and

constructive pedagogical practices that boost student engagement, lend credence to this view. Likewise, Zhang et al. (2020) discovered that learners' motivation, personal connection and engagement increased when learners were involved in OEP-based learning.

While OER and OEP mainly aim at access, participation and contextual relevance, UDL complements these approaches by targeting the inclusive design of learning environments. UDL provides for variability in learners regarding language, knowledge, preferences, and socioeconomic circumstances, through multiple means of engagement, representation, and action and expression. This perspective is especially important in participating African countries, where the diversity of languages and the lack of equal access to education often restricts learners' ability to express their knowledge of STEM. Orndorf et al. (2022) state that UDL offers practical strategies for making classrooms more welcoming to all students and a useful framework for analysing the efficacy of different pedagogical approaches in various settings. SDL also further completes the framework by enhancing learner autonomy, critical thinking, reflection and independent problem solving. When learners are supported to identify their learning needs, access the right resources, monitor their progress and use feedback effectively, they become active participants in the learning process.

Within the framework of TIMSS, SDL offers a conceptual way to overcome the barriers of learner agency, limited formative assessment, and passive learning through increased engagement, reflective practice, and independent learning. In line with this focus on learner autonomy, adaptive learning technologies and AI-supported tutoring systems may further support SDL through personalised feedback and learning pathways that respond to learners' individual learning needs. However, as discussed in the conceptual framework, the contribution of these technologies depends on enabling conditions such as adequate infrastructure, capacity of teachers, policy support and fair access to digital technologies.

To summarise, the literature suggests that these perspectives are complementary rather than interchangeable. OER and OEP increase access to localised and participatory learning opportunities; UDL advances inclusive instructional design that caters to learner diversity; and SDL enhances learner agency and self-regulation. The proposed conceptual framework demonstrates how these interrelated approaches offer complementary mechanisms for addressing structural and pedagogical barriers related to TIMSS underperformance. Instead of promoting a singular solution, the framework shows how enhancing access to contextually relevant educational resources, creating more inclusive learning settings, and cultivating learner autonomy can, perhaps, work together to generate more equitable and engaging STEM educational experiences. This literature synthesis is consistent with Mokgwathi et al. (2025) and suggests that equitable STEM outcomes depend on more than just access to educational resources, but also on the quality, cultural relevance, inclusiveness, and pedagogical use of those resources.

Research Question Two:

What structural, curricular, and pedagogical factors does the literature identify as contributing to TIMSS underperformance in participating African countries beyond measured achievement scores?

The reviewed literature suggests that the underperformance of TIMSS in participating African countries is a combination of structural, curricular and pedagogical factors that transcend achievement scores measured. Unequal learning opportunities due to disparities in school infrastructure, access to digital technologies, and availability of quality STEM learning resources continue to be created, especially between urban and rural schools.

From a curriculum perspective, the limited localisation of learning materials and use of standardised curricula often reduce learners' ability to relate STEM concepts with their linguistic, cultural and everyday experiences. From a pedagogical point of view, the literature indicates that in predominantly teacher-centred pedagogical approaches there may be reduced opportunities for inquiry, collaboration and active knowledge construction and thus the development of the reasoning and problem-solving competencies highlighted in TIMSS is constrained.

Consistent with these results, Nyamunda (2025) identified instructional time, learner-teacher ratios and linguistic diversity as significant predictors of TIMSS performance, whilst Taylor (2021) and Mokgwathi (2025) argue that persistent achievement gaps are indicative of larger systemic inequalities tied to socio-economic conditions, teacher preparation and curriculum implementation. This suggests that TIMSS underperformance is influenced by learners' knowledge and skills but also by the wider educational environment in which teaching and learning occur.

Research Question three:

What are the implications of this conceptual framework for promoting equitable and inclusive STEM learning in participating African countries?

The conceptual framework developed in this study has important implications for promoting equitable and inclusive STEM learning in the participating African countries. The framework integrates OER, OEP, UDL and SDL in an effort to re-conceptualise the underperformance of TIMSS as a consequence of structural, curricular and pedagogical conditions rather than solely of learners' abilities. This perspective emphasises that equitable STEM learning requires improved access to high quality and localised learning resources, inclusive learning environments that respond to learner diversity and learner agency thru active participation and self-directed learning. These complementary approaches provide a holistic view to address persistent barriers to STEM learning while enabling more inclusive and engaging educational experiences.

The framework also suggests that equitable STEM learning depends on the creation of enabling environments that allow for successful implementation of Open Education. This includes improving teacher professional development, enhancing digital infrastructure, supporting curriculum localisation and developing policies that encourage inclusive and learner-centred pedagogical practices. The framework acknowledges the interdependence of these conditions and offers a coherent basis to promote educational equity through improved access, participation and meaningful engagement in STEM learning. These implications guide the subsequent recommendations for research, practice, and policy.

5. Implication and recommendation

5.1 Implications for research

This conceptual model provides several avenues for further empirical investigation. First, more research is needed to investigate the proposed mediating mechanisms, including the interaction effects of contextualised OERs, OEP and AI-enabled feedback to affect STEM learning outcomes in line with cognitive domains assessed in TIMSS. Longitudinal and quasi-experimental research designs might be applied to systematically explore the impact of OER/OEP integration on students' higher-order thinking, inquiry skills and conceptual understanding over time.

Future research should explore the development of self-directed learning practices in open learning environments in African contexts, particularly in areas with poor digital infrastructure. The relationship between language localisation and conceptual clarity, and how this affect learner performance, needs to be investigated in particular, since linguistic characteristics have a strong impact on TIMSS results. Researchers might also investigate the systemic and institutional factors that promote or inhibit the adoption and successful use of OER, OEP, and AI-enabled tools in STEM classrooms. These studies will provide evidence-based suggestions for improving STEM learning environments and support the empirical validation and improvement of the suggested model.

5.2 Implications for practice

The incorporation of OER into the classroom setting provides an opportunity to follow a viable route in the reduction of disparities in access to quality STEM resources. Educators and school systems must go beyond ensuring the adoption of OER and look at their localisation and contextualization to be relevant to the linguistic, cultural and curriculum background of learners. This necessitates the teachers to recognize, adapt and successfully incorporate OER into the teaching process. Also, the principles of the UDL have a major impact on the inclusive pedagogy. Teachers ought to be motivated to create learning experiences that offer a variety of engagement, representation, and expression; therefore, supporting the needs of a variety of learners and decreasing obstacles to participation. Professional development programs must thus be directed to help teachers with effective strategies of applying flexible and inclusive teaching methods in STEM classrooms. SDL can be promoted in STEM education to improve learner independence, critical thinking, and academic growth in the long

term. Teachers are encouraged to provide learners with chances to participate in inquiry-based, problem solving, and reflective learning experiences, which are reinforced by prompt and positive feedback. Such a change in the direction of learner-centred pedagogy demands a reorientation of classroom activities towards the delivery of content to the learner, rather than facilitating the learning process.

5.3 Implications for policy

The proposed approach underscores the necessity of a coherent, system-wide commitment to integrating technology-enhanced pedagogies and ensuring transparency within national STEM policy frameworks. At the ministerial level, education authorities should establish regulatory and legislative provisions that promote the creation, contextual adaptation, and widespread dissemination of OERs across all grade levels, with particular emphasis on science and mathematics education. Policy instruments should explicitly support OEP, including the systematic peer review of instructional materials, structured collaboration among teachers, and the implementation of open assessment approaches that enhance feedback literacy for both educators and learners.

To promote equitable access to high-quality STEM learning opportunities across diverse educational contexts, sustained investment in digital infrastructure is essential. Such investment should encompass the development and deployment of low-bandwidth digital platforms and artificial intelligence-supported learning tools that can operate effectively in resource-constrained environments. Also, plans aimed at improving performance in the TIMSS should explicitly incorporate pedagogical reforms informed by OER and OEP.

These reforms should align classroom practices with the constructs and competencies assessed by TIMSS, thereby strengthening the coherence between instructional processes and assessment outcomes. To ensure that system-level reforms are both evidence-informed and contextually relevant, policy frameworks should encourage and institutionalise research-practice partnerships. These collaborations should systematically evaluate the effectiveness and equity implications of openness and AI integration in STEM education, thereby generating robust evidence to guide iterative policy refinement.

6. Recommendations

Based on the proposed model and its potential to strengthen STEM learning outcomes, the following recommendations are offered:

For Teachers and Educators:

1. Encourage the methodical incorporation of OERs and OEP into the STEM curriculum, with an emphasis on contextualising, localising, and adapting learning materials to several languages.
2. Integrate learner agency, metacognition, and reflection – all self-directed learning competencies into STEM education and assessment techniques.

For school and curriculum developers:

3. Incorporate open pedagogy, inquiry-based learning, digital content creation, feedback literacy, and AI-enhanced assessment processes into teacher professional development.

For Teacher Education and Professional Development Providers:

4. The training programs should focus on equipping instructors with the skills they need to create inclusive learning activities in accordance with UDL principles; and modify and incorporate OER into their teaching.
5. Facilitate learner-centred and inquiry-based methodologies that enhance SDL.

For Ministries of Education Policy Makers:

6. Create frameworks for policies that require or promote the production, distribution, and review of OER at the national and regional levels.
7. Invest in digital infrastructure, paying particular attention to low-bandwidth solutions that facilitate fair access to open and AI-enabled learning environments.

For Research and Research Institutes:

8. Conduct empirical studies to test, refine, and contextualise the proposed conceptual model across diverse African educational settings.

7. Conclusion

The study emphasises the significance of going beyond TIMSS scores when considering the educational factors influencing the performance of participating African countries. It also explores the potential of OEP to address some of these challenges. The persistent difficulties—such as language barriers, resource constraints, rigid curricula, and inadequate infrastructure—highlight structural problems that limit STEM education in the participating African contexts. OER, SDL and UDL can provide complementary approaches to creating more inclusive and learner-centred education environments, but the potential of technology-enhanced pedagogies is contingent on equal access to digital infrastructure, connectivity and the skills for meaningful technology use. The evidence provided corroborates that OEPs not only facilitate curriculum adaptation and decolonization but also empower learners to assume control over their educational experiences.

Conflict of Interest

The authors declare no conflict of interest.

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