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Enhancing STEM Competency and Educational Equity in Rural Schools Through PhET Simulations and Teacher Development

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Abstract
The persistent STEM education disparities in rural Kenyan schools are compounded by infrastructural constraints, underprepared teachers, and low learner engagement, particularly among girls. This study evaluated the impact of localized PhET simulations integrated with structured teacher development on instructional practices, self-efficacy, and learner STEM competency under Kenya's Competency-Based Curriculum (CBC). A convergent mixed-methods design was employed, involving 18 teachers from a rural primary school who participated in a professional development intervention. Quantitative data showed significant gains in teacher self-efficacy (from 2.4 to 4.1) and learner performance (from 45% to 71%), while qualitative findings revealed increased learner engagement, improved use of inquiry-based pedagogy, and infrastructural challenges such as electricity outages and limited digital fluency. The findings underscore the potential of PhET simulations as an equity-driven pedagogical tool in low-resource CBC settings. The study recommends institutionalization of simulation-based training, offline content delivery, and sustainable infrastructure investments to foster inclusive STEM education in rural schools.

Keywords: *PhET simulations, STEM competency, CBC, teacher development, educational equity*

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I. BACKGROUND

The global outcry for improved and equitable STEM education is underscored by persistent low learner outcomes coupled with gender and resource-based disparities. Despite policy commitments, performance in STEM subjects continues to remain lower than other subjects, and women constitute only 35% of STEM graduates globally, a figure that has remained unchanged over the past decade (UNESCO, 2024a). In Africa, women in science industries and academia comprise 30%, reflecting systemic barriers to participation and progression of women in STEM fields (UNESCO, 2024a). The persistent dwindling numbers of women along the STEM pathways, as they progress through successive educational levels reflects the “leaky pipeline” that manifests globally. Moreover, while women now account for the majority of university students in many countries, they remain underrepresented in STEM disciplines, a discrepancy that begins in basic education and widens at each educational transition (UNESCO, 2024b; UNESCO, 2025).

In sub-Saharan Africa, curricula have begun embracing competency-based frameworks and Kenya has not been left behind. In Kenya, the 2017 introduction of the CBC aims to promote critical thinking, creativity, collaboration and problem-solving among learners. Kenya’s Competency-Based Curriculum (CBC), emphasizes experiential learning even though rural schools remain under-resourced, with inadequate laboratory facilities and limited digital infrastructure. Consequently, implementation in rural contexts is hampered by teacher efficacy and infrastructural deficits (KICD, 2021). Early reviews indicate that when teachers receive CBC-aligned training in inquiry-based science pedagogy, learners report higher enjoyment and participation in science activities (Government of Kenya, 2024). Nationally, many rural schools lack the instructional materials needed to fully implement CBC science modules. These inequities contravene Kenya’s Vision 2030 goal to cultivate a knowledge-based economy through inclusive STEM education.

Globally, empirical studies reveal significant gains in primary students’ learning outcomes when PhET is integrated into instruction (Salim, Daher & Diab, 2024). Empirical grounding of PhET’s efficacy is demonstrated in studies that show how PhET improves learning in similar under-resourced contexts (Kwenani & Morake 2020; South Africa; Baser & Durmus, 2010 and Turkey and Wambugu et al., 2018). Digital simulations such as PhET interactive simulations and LabXchange digital resources are freely accessible evidence-based teaching and learning tools that help the learner to visualize abstract concepts. Moreover, a 2024

PhET Impact Report revealed that simulations aligned with an equity framework can reduce conceptual gaps and promote inclusive engagement (PhET Impact Report, 2024). Equity framework positions integration of simulations in teaching and learning as a driver of social justice and innovation, hence presents an opportunity to address the existing STEM education inequalities (Freire, 1970) in Kenya. Consequently, education policymakers, curriculum developers, and donor agencies must collaborate to embed simulation-based pedagogies in the national CBC implementation strategies, ensuring resource allocation and teacher support systems address contextual challenges.

Statement of the problem

Globally, despite concerted efforts to promote inclusive education, disparities in STEM learning opportunities remain deeply rooted. Socio-economic inequities, pervasive gender biases, and uneven distribution of qualified teachers and instructional resources continue to restrict broad-based engagement in STEM fields (UNESCO, 2023). As a result, learners from rural under-served communities encounter persistent barriers that limit both their participation and achievement in STEM.

Within Sub-Saharan Africa, these global trends are magnified by systemic impediments. Under-resourced school infrastructures, inadequate teacher preparation in STEM disciplines, and insufficient access to digital technologies collectively imped the effective implementation of learner-centered pedagogies (World Bank, 2022; Oketch et al., 2021). In particular, students in rural under-resourced schools face the greatest exclusion. They often attend schools lacking basic laboratories and equipment and or technological infrastructure including weak internet connectivity, and are taught by teachers who have received minimal or no preparation in innovative STEM instructional methods.

In Kenya, the transition to a Competency-Based Curriculum (CBC) demonstrates the governments commitment to fostering critical thinking and practical skills. However, rural and public schools frequently lack the infrastructure, instructional materials, and suitably trained teachers required to realize CBC's STEM teaching and learning objectives. Reports indicate that many learners have minimal exposure to functioning laboratories, limited interaction with female STEM role models, and restricted access to digital tools. Additionally, persistent gender imbalances, illustrated by low female enrollment rates of 48.4% and below at the secondary level, compound the challenges female learners face, leading to even lower female representation in tertiary STEM programs, industries, and academia. Empirical evidence suggests that without targeted, equity-driven interventions, rural students will continue to under-engage with CBC's STEM competencies, thereby perpetuating a cycle of exclusion in STEM education and related opportunities.

In the absence of strategic, context-specific solutions, these multifaceted disparities threaten to widen over time, positioning both national and international commitments to equitable STEM education in jeopardy. To address this problem, interventions that directly confront barriers to access, strengthen teacher capacity for application of interactive and inclusive STEM pedagogy and simulations, and promote gender equity, will ensure that STEM serves as a catalyst for opportunity rather than a mechanism of exclusion.

Research question

How does the integration of localized PhET simulations and structured teacher development influence instructional practices, teacher self-efficacy, and learner STEM competency in rural Kenyan primary schools under the CBC framework?

Research objectives

1. To evaluate the effect of structured professional development on teacher self-efficacy and inquiry-based instructional practices using PhET simulations in rural CBC classrooms.
2. To assess the impact of integrating PhET simulations on learners' engagement, conceptual understanding, and STEM competency in under-resourced primary school settings.
3. To identify the institutional and contextual barriers affecting the effective implementation of PhET simulations and propose strategies for scalable and sustainable integration in rural schools.

II. LITERATURE REVIEW

Introduction

This section examines global, regional, and Kenyan studies on integration of PhET simulations in teaching an, teacher development, and STEM equity, aligned to the central research question: How does the integration of localized PhET simulations and structured inquiry-based teacher training influence STEM instructional practices, teacher efficacy, and learner engagement under CBC?

Digital simulations and STEM competency

The increasing global emphasis on equitable and quality STEM education has necessitated the integration of innovative STEM pedagogies and simulations that align with 21st-century learning demands. The Competency-Based Curriculum (CBC) in Kenya aims to nurture creativity and critical thinking, problem-solving, and communication and collaborative skills in learners (KICD, 2021). However, the successful implementation of CBC, especially in rural under-resourced schools, requires the integration of practical, low-cost, and scalable pedagogical tools. Digital simulations such as PhET and platforms like LabXchange have emerged as critical technologies in advancing STEM pedagogy within under-resourced contexts.

In particular, the LabXchange and PhET Interactive digital resources offer free research-based interactive tools for STEM subjects and have demonstrated efficacy in enhancing conceptual understanding through visual, interactive interfaces. Adams, Paulson & Wieman (2021) report significant improvements in conceptual understanding especially when PhET simulations are used alongside inquiry-based models. In sub-Saharan contexts, Omwenga and Were (2023), conducted a study in western Kenya and found that PhET simulations enhanced learners' comprehension of abstract science concepts like electricity and chemical reactions through the provisions of visual models. Visual models are known to bridge theory and practice. Notably, these tools also reduced the cognitive load associated with rote memorization because they promote visualization and experiential learning. Additionally, digital simulations have potential to mitigate resource constraints by providing virtual laboratory experiences for schools that have no laboratories and the associated equipment. Consequently, it is imperative that simulation-based modules are embedded in teacher education programs to strengthen pedagogical capacity for STEM instruction in resource constrained schools.

Professional teacher development for digital pedagogy

The PhET and LabXchange platforms offer custom-made learning pathways, assessments, and virtual lab experiences (Mutai & Kamau, 2022). Studies conducted show that when labXchange digital resourced are integrated into CBC-aligned instructional methods, learner agency and differentiated instruction are promoted so that students learn at their own pace. When teachers integrate LabXchange digital resources in their teaching they are able to effectively scaffold instruction, assign personalized modules, and track learner progress through in-built analytics. Research by Mugendi (2022) emphasizes the benefits of peer learning and mentorship in supporting the adoption of simulations in teaching. Schools that fostered collaboration among teachers realized higher integration rates and improved learner outcomes. This aligns with the collaborative models promoted by Critical Pedagogy (Freire, 1970). Critical Pedagogy holds that learners and teachers are co-constructors of knowledge. Equally, according to a study conducted by Kirwa and Kiplangat (2020) CBC-aligned assessment practices must be transformed to incorporate performance-based evaluations so that CBC aligns with the experiential nature of simulations.

Notably, effective integration of simulations in teaching requires that STEM subject teachers undergo continuous, context-sensitive professional development. Mwangi, Okoth & Kiptoo (2024) argue for embedded learning experiences over one-off workshops to foster teacher self-efficacy and sustainable classroom practices. Mugendi (2022) highlights peer mentorship as a catalyst for simulation adoption. This aligns with Vygotsky's sociocultural theory that positions learning as mediated by social interaction. Nevertheless, Wafula & Otieno (2021) found that digital exposure and fluency is persistently low among teachers in rural under-resourced schools. Limited digital exposure and fluency creates a critical training gap. To bridge the training gap, stakeholders must design and fund ongoing, mentorship-based professional development initiatives so as to build digital literacy and pedagogical adaptability.

Equity outcomes of simulations

Gender equity remains a focal concern in STEM education, course enrolment and at in STEM-related industries and academia. A study conducted by Akoth, Wekesa & Musyoka (2023), found that simulations can bridge gender disparities in STEM learning by providing equitable, non-biased, and inclusive learning environments. The study further revealed that girls in rural Kenyan schools responded positively to digital tools, and reported increased confidence and interest in science subjects. These findings demonstrate the transformative potential of simulations not only as STEM pedagogical tools but as equity interventions.

STEM Simulations have potential to serve as equity interventions by providing accessible, non-biased learning platforms. Akoth et al. (2023) demonstrated increased confidence and engagement among girls using PhET simulations, reducing gendered participation gaps. Critical pedagogy frameworks (Freire, 1970) further support the role of simulations in democratizing knowledge construction and empowering marginalized learners. This further demonstrated by development of equity-focused guidelines for simulation integration that prioritize gender-sensitive pedagogies and inclusive design principles.

Regional and Kenyan contexts

In the Kenyan context, inadequate technological infrastructure and pedagogical limitations continue to hinder the integration of digital resources in teaching and learning. Wafula and Otieno (2021) point out that many rural teachers have no prior exposure and experience with digital resources and tools, hence they lack the digital literacy to integrate simulations effectively. Mwangi et al. (2024) argue that professional development must be continuous with embedded learning experiences that address teachers' contextual realities. These insights align with sociocultural learning theory, which posits that learning is mediated by tools and social interaction (Vygotsky, 1978). A study conducted by Kirwa & Kiplangat (2020) posit that the need to adapt assessment practices for experiential learning is a core feature of CBC and simulations. However, systematic adoption remains limited by policy inertia and resource allocation challenges. Oyugi & Wanjala (2021) recommend policy reforms such as preloaded simulation content on solar-powered devices to address connectivity issues. This implies advocacy for policy reforms that require clear digital simulation standards be embedded into the teacher education curricula and CBC guidelines.

Gaps in the reviewed literature

While evidence affirms the benefits of integrating STEM simulations and professional development, longitudinal assessments of sustainability, comparative analyses between rural and urban implementations, an investigation of localized customization of simulations still show glaring theory-practice gaps. Additionally, limited research examines the long-term impact on equity metrics beyond initial engagement and performance gains, and whether they experience comparable opportunities and outcomes to their peers. The studies show that despite promising outcomes, a gap persists between availability and actual classroom integration. To address the gaps, Oyugi and Wanjala (2021) recommend institutional policy reforms that integrate simulation-based pedagogy into teacher education curricula. Additionally, they emphasize the need to decentralize digital content distribution through preloaded resources and solar-powered devices. These reforms are crucial in ensuring sustainability and scalability.

Recent studies affirm that when digital simulations are embedded in teacher training curricular and CBC implementation, improve the quality of STEM teaching, learner performance, and equity. However, the success of adoption depends on the context-sensitive implementation strategies applied, teacher support systems, and infrastructure investments. Therefore, to institutionalize digital simulations in CBC STEM education in Kenya, researchers, practitioners, and policymakers must co-develop contextualized strategies.

III. METHODOLOGY

Research design

This study adopted a convergent mixed-methods design to capture both measurable impacts and contextual holistic insights into pedagogical interventions. Mixed methods is applied to integrate quantitative measures of efficacy with qualitative insights into contextual factors (Creswell & Plano Clark, 2018). The study context was a rural under-resourced primary school in Kenya. A total of 18 STEM subject teachers participated in the three-session professional development program with the aim of integrating PhET simulations into teaching and learning. The teachers were purposively sampled based on their involvement in CBC implementation (Palinkas et al., 2015).

Quantitative data were collected via a pre- and post-intervention teacher self-efficacy and learner engagement survey (Tschannen-Moran & Hoy, 2001). Qualitative data were obtained through focus group discussion, lesson observations checklist, and document analysis (Krueger & Casey, 2015). The research instruments were grounded in context to capture authentic teacher and learner experiences in the school. Data were collected over a fourteen-week intervention period.

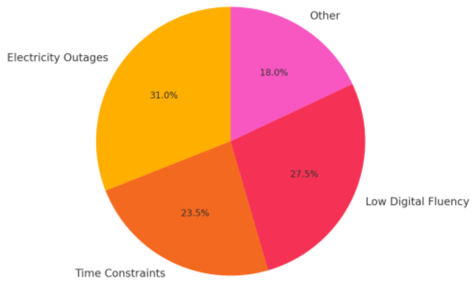
Quantitative data were analyse using paired-sample t-tests while qualitative data were coded thematically using NVivo (Braun & Clarke, 2006).

IV. FINDINGS

Teachers' perceptions and institutional barriers

Quantitative data analysis revealed a baseline average teacher self-efficacy scores of 2.4, rising to 4.1 post-training on a 5-point Likert scale. The finding identified barriers to teacher self-efficacy as technological infrastructure including electricity outages and (reported by 62%), time constraints (47%), and limited digital fluency (55%).

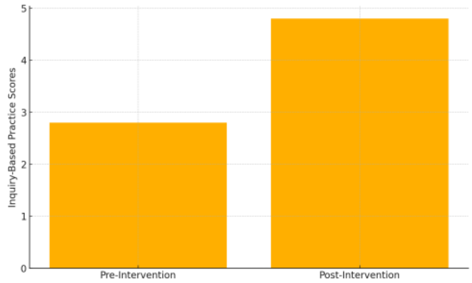
Figure 1. Key Institutional Barriers to PhET Integration



Impact on instructional practices and teaching self-efficacy

The post-intervention findings showed a 71% increase in teacher use of inquiry-based strategies aligned to CBC competencies (mean pre=2.8, post=4.8; $t(17)=9.3$, $p<.001$). Notably, classroom observations registered an enhanced use of guiding questions and scaffolded learning sequences.

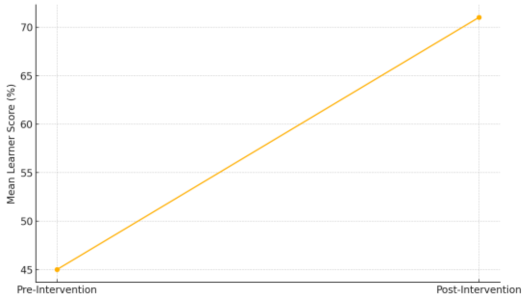
Figure 2. Teacher Self-Efficacy and Inquiry-Based Practice Scores



Effect on learner STEM competency

Averagely, the learner assessment scores were found to improve from a mean of 45% pre-intervention to 71% post-intervention ($t(89)=12.7$, $p<.001$). Learner engagement increased from 2.8 to 4.5. Evidently, this reflects a shift from passive to active learning among learners during simulation activities.

Figure 3. Learner STEM Performance Pre- and Post-Intervention



V. DISCUSSION

Teachers' perceptions and institutional barriers

Generally, the study findings indicate that PhET simulations have a measurable positive effect on classroom practices and learner outcomes. This implies that investments in interactive STEM pedagogy and digital resources are essential to raise the quality of STEM teaching and engagement in resource-limited contexts.

Additionally, the interviews conducted and classroom observations done revealed three major themes namely; (i) increased learner engagement and participation, (ii) increased teacher self-efficacy through exposure to new pedagogical tools, and (iii) challenges related to technological infrastructure, time constraints due to the rigidity of the school teaching schedules, and digital fluency. The teachers interviewed reported that simulations sparked curiosity among learners and the scientific phenomena and process were easier to demonstrate and explain. This made it easy for learners to access the abstract scientific concepts. However, the frequent power outages, weak internet connectivity and time constraints limited consistent integration of the STEM pedagogical tools. Localized barriers such as digital illiteracy and technological infrastructural limitations highlight the importance of tailoring interventions to community-specific realities. This findings corroborate the global evidence on technological infrastructural barriers and the rigidity of the teaching schedules (Wafula & Otieno, 2021), and reinforce calls for programmatic support in the provision of offline access to simulations, flexible teaching schedules for digital pedagogy implementation, and integration of solar-powered devices.

Instructional practices and self-efficacy

Consistent with Crespo et al. (2022), enhanced teacher self-efficacy translated to more frequent use of interactive student-centered pedagogical strategies and tools as evidence of improved digital skills acquisition among the science teachers. This paradigm shift aligns with Vygotskian principles of mediated learning (Vygotsky, 1978). The improvements in self-efficacy and subsequent increase in learner scores, mirror outcomes in other CBC-aligned research settings in sub-Saharan Africa. Based on this finding there is need to embed and scale simulation-based and reflective practice modules in the professional development programs for teacher learning to standardize enhanced learning pathways and sustain efficacy gains.

Learner STEM competency

The improved learner outcomes mirror Salim et al.'s (2024) findings in elementary contexts, extending the evidence base to rural CBC settings. Additionally the findings align with studies by Adams et al. (2021) and Omwenga & Were (2023), who demonstrated that PhET simulations are key in facilitating conceptual clarity and learner motivation. Integrating critical pedagogy principles, the intervention advanced equitable access and student-centered approaches, and therefore national roll-outs of digital learning tools should include equity-focused implementation strategies informed by local research.

VI. CONCLUSION

Teacher perceptions and the identified barriers in the study highlight critical infrastructural and systemic challenges that must be addressed in order to institutionalize simulation-based pedagogy. Enhanced teacher self-efficacy and the shift in instructional practices demonstrate that structured training is a catalyst for adoption of inquiry-based practices. Significant gains in learner science competency confirm the pedagogical value of PhET simulations in resource-constrained CBC environments. This study further demonstrates that integrating PhET simulations into CBC-aligned science teaching can significantly improve instructional quality, learner engagement and performance in rural schools. The flexibility of PhET tools, the offline access capability, and curriculum relevance to CBC make simulations an asset for equity-driven science reforms in rural under-resourced primary schools. Moreover, teacher capacity development when aligned with practical low-cost digital tools, can effectively address resource constraints and shift pedagogical mindsets toward interactive learner-centered teaching and learning. Thus stakeholders should embed simulation-based instruction in both preservice and in-service teacher development frameworks.

VII. RECOMMENDATIONS

To advance STEM competency and equity through the integration of PhET simulations and teacher development in rural schools, it is imperative first to design and implement targeted digital literacy and simulation integration training programs tailored specifically for teachers in rural and under-resourced contexts. The training should be designed to equip science teachers with the requisite skills to navigate, deploy, and adapt PhET simulations in contexts where technological infrastructure and pedagogical support may be limited. Concurrently, efforts must be made to institutionalize PhET interactive simulations within both pre-service and in-service teacher education curricula. This will ensure that the use of PhET simulations aligns seamlessly with the Competency-Based Curriculum (CBC) and national education standards. Embedding simulation-based pedagogies in formal teacher preparation and professional development programs will foster systemic uptake and sustainability.

Secondly, to address the diverse needs of learners and schools operating in under-resourced contexts, localized, offline-accessible simulation packages that integrate contextual phenomena drawn from the curriculum, and which maximize relevance and accessibility, should be given preference. Similarly, facilitating access to sustainable energy solutions in rural schools is essential to mitigate electricity-related barriers that impede the utilization of digital resources in teaching and learning. Finally, establishing and nurturing continuous Professional Learning Communities (PLCs), and peer mentorship frameworks, will promote reflective practice, foster collaborative learning, and sustain pedagogical innovation in simulation-based STEM instruction. By supporting teachers in sharing best practices, reflecting on the implementation challenges, and re-strategizing, the PLCs will help ensure that the integration of PhET simulations leads to lasting improvements in teaching and learning.

AREAS FOR FURTHER RESEARCH

To build on the findings of this study and support the continued advancement of equitable STEM education in rural schools, the following areas are recommended for further scholarly investigation:

Longitudinal impact assessments

Undertake longitudinal studies to evaluate the sustainability, scalability, and long-term educational impacts of PhET simulation integration within Competency-Based Curriculum (CBC) classrooms in rural contexts. Such studies will provide insight into the durability of simulation-based pedagogical gains across multiple academic cycles.

Gender-specific learning outcomes

Investigate gender-differentiated learning outcomes linked to the use of PhET simulations, with a focus on how interactive simulations influence participation, confidence, and achievement among male and female learners. This research will contribute to strategies for advancing gender equity in STEM education.

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Conflict of Interest Statement
The author declares no conflict of interest with respect to the authorship and/or publication of this article.

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