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Influence of Teacher Engagement with PhET Simulations on Learner Engagement and Conceptual Understanding in Science

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Abstract
This study investigated the influence of teacher engagement with PhET Interactive Simulations on learner engagement and conceptual understanding in secondary school science classrooms within rural, under-resourced settings in Western Kenya.
Anchored in constructivist and social constructivist theories, the research adopted a convergent parallel mixed-methods design involving teacher and learner questionnaires, classroom observations, focus group discussions, and pre- and post-tests. The study was conducted across six public secondary schools in Bungoma and Kakamega counties, with 24 science teachers and approximately 1,320 Form Two learners participating.
Quantitative findings revealed that 63% of teachers integrated PhET simulations in at least three weekly lessons, while 77% of learners actively engaged during PhET-enhanced instruction. Learners demonstrated a 28-point mean improvement in test scores, with 84% self-reporting enhanced conceptual clarity. Regression and correlation analyses established a statistically significant relationship ($r = .57$, $p < .01$) between teacher engagement and learner gains. However, challenges such as limited access to digital devices (71%), inadequate professional development (68%), and curriculum rigidity were notable barriers.
The study concludes that teacher engagement with PhET simulations significantly enhances learner participation and conceptual understanding when accompanied by structured facilitation and scaffolding. It recommends embedding simulation-based pedagogical training in pre-service and in-service programs, expanding access to offline simulations, revising science curricula to incorporate simulations, and institutionalizing EdTech support in national education policy to advance equity and quality in STEM education.
Keywords: *Teacher Engagement, PhET Simulations, Learner Engagement, Conceptual Understanding, Science Education, Digital Pedagogy*

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I. INTRODUCTION

The integration of digital technologies in education has transformed how science concepts are communicated, making teaching more interactive and learner-centered. Tools such as virtual simulations, mobile apps, and digital labs are increasingly used to bridge abstract concepts and real-life experiences, enhancing engagement and learning outcomes (Penn & Ramnarain, 2019). Among these tools, PhET Interactive Simulations provide free, research-based resources that foster inquiry-based learning through visualization and exploration.

PhET simulations are particularly relevant in the Kenyan science education context. The Competency-Based Curriculum (CBC) emphasizes learner-centered approaches and practical application of knowledge. However, many schools lack laboratory infrastructure, making it difficult to deliver hands-on learning experiences. In this context, PhET offers an accessible, cost-effective alternative for visualizing scientific phenomena and promoting critical thinking. Initiatives by the Ministry of Education and development partners are gradually supporting the adoption of EdTech tools like PhET, especially in underserved schools.

This study seeks to contribute to the literature by exploring how different modes of teacher engagement with PhET simulations—before, during, and after instruction—influence learner participation and conceptual understanding. Due to the evolving nature of educational technology, teacher engagement practices must also adapt to ensure technology implementation leads to meaningful learning (Almasri, 2022).

1.2 central research question
How does teacher engagement with PhET Interactive Simulations influence learner engagement and conceptual understanding in science education?

1.3 research objectives
1. To assess the levels of teacher engagement with PhET Interactive Simulations in science classrooms.
2. To determine the impact of teacher engagement with PhET on learner engagement.
3. To evaluate the relationship between teacher engagement and learners' conceptual understanding in science.
4. To identify challenges and enablers in implementing PhET simulations in science instruction.

II. LITERATURE REVIEW

2.1 Introduction

The integration of digital tools in science education has transformed traditional instructional approaches by introducing learner-centered technologies that promote interactivity and visualization. PhET Interactive Simulations, developed by the University of Colorado Boulder, have been instrumental in reshaping science pedagogy globally. Numerous studies affirm their potential in enhancing learner engagement and supporting deep conceptual understanding when used effectively by teachers (Perkins et al., 2021; Chukwu & Sam, 2022). However, there remains a gap in understanding the direct role of teacher engagement with simulations, particularly in under-resourced contexts such as Kenya. This literature review explores theoretical and empirical insights on teacher technology integration, simulation-based science instruction, and their influence on student learning outcomes.

2.1 Theoretical framework on engagement and conceptual understanding

The theoretical underpinning of this study draws from constructivist and social constructivist learning theories. Constructivism posits that learners build knowledge actively through experience and reflection (Piaget, 1972), while social constructivism, championed by Vygotsky, emphasizes learning through social interaction and scaffolding (Vygotsky, 1978). PhET simulations are grounded in these principles—they offer inquiry-based, visually interactive environments where learners explore scientific concepts dynamically (Wieman et al., 2010; Podolefsky et al., 2018). Such environments stimulate cognitive engagement and conceptual development by allowing learners to visualize abstract phenomena and manipulate variables in real-time.

Furthermore, the ICAP framework (Chi & Wylie, 2014), which categorizes engagement into Interactive, Constructive, Active, and Passive modes, provides a lens for examining how teacher-directed simulation tasks can promote constructive and interactive engagement—known to yield the highest learning gains. When teachers engage deeply with simulations—designing inquiry tasks, modelling use, and facilitating discussion—they support students' transition from passive observation to active construction of knowledge (Kastberg et al., 2021).

2.2 Teacher engagement with educational technology

Teacher engagement with educational technology encompasses attitudes, knowledge, and instructional practices. According to Tondeur et al. (2018), effective integration of ICT tools like PhET requires more than access; it demands pedagogical content knowledge, training, and a positive orientation toward technology. In classrooms where teachers are digitally competent and confident, student-centered instructional practices are more prevalent, and learner engagement is heightened (Stols et al., 2020).

Recent evidence underscores the importance of teacher agency and digital pedagogy in simulation use. For instance, Sahin and Yilmaz (2022) found that teachers who engaged in professional development tailored to simulation-based instruction reported increased efficacy and creativity in lesson planning. Additionally, teacher modelling of simulation use significantly shapes student attitudes and behaviors toward science learning (Akpan et al., 2023). In the Kenyan context, Wekesa and Ndiku (2022) demonstrated that digital readiness and training of teachers positively influenced the integration of simulations in science instruction. Similarly, Nyambura and Mburu (2021) found that professional development workshops enhanced teacher digital competencies in rural counties, leading to improved learner engagement.

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2.3 The role of PhET interactive simulations in science education

PhET simulations have become an internationally recognized resource in science classrooms, offering dynamic representations of phenomena across physics, chemistry, and biology. Their effectiveness is well-documented in improving conceptual understanding, especially in topics that are abstract or difficult to demonstrate through traditional methods (Perkins et al., 2021). Simulation-based instruction promotes active learning, reduces misconceptions, and encourages self-paced exploration (Adams et al., 2020; Phan et al., 2021).

Moreover, PhET simulations support differentiated instruction by catering to diverse learner needs and offering multiple representations of content (McKagan et al., 2020). Teachers who integrate these simulations meaningfully tend to design inquiry-based tasks and formative assessments that boost learner autonomy and motivation (Yakin & Tinmaz, 2019).

2.4 Teacher engagement and learner outcomes

Emerging research emphasizes the direct correlation between teacher engagement with simulations and improved learner outcomes. Studies have shown that when teachers are involved in co-designing lessons, guiding exploration, and facilitating reflection during simulation use, students demonstrate higher engagement and deeper conceptual grasp (Gupta & Pandey, 2023; Okereke et al., 2022). For instance, in a study by Wambugu and Githua (2019), Kenyan secondary students taught using PhET simulations with active teacher facilitation scored significantly higher in post-tests compared to those in lecture-based classes.

Furthermore, teacher-led simulation implementation aligns with the Universal Design for Learning (UDL) framework, which advocates for multiple means of representation, engagement, and expression—leading to more inclusive science instruction (CAST, 2021).

2.5 Challenges in low-resourced settings

Despite the promise of simulations, implementation remains a challenge in many Sub-Saharan African schools due to infrastructural, pedagogical, and policy-related constraints. Teachers often face barriers such as lack of internet, insufficient digital devices, limited training opportunities, and curriculum rigidity (Jukes et al., 2020; Mwarari & Mugambi, 2021). These issues restrict not only the frequency of simulation use but also the depth of teacher engagement with them.

Additionally, studies in rural Kenya and Uganda point to systemic gaps, including low institutional prioritization of ICT integration and minimal support structures for teacher capacity development (Otieno et al., 2023). Wambua and Ngugi (2022) identified that electricity unreliability and lack of offline simulation access hinder regular usage of tools like PhET in Kitui and Kakamega counties. In Tanzania, Mwambene et al. (2021) highlighted that lack of ICT policy enforcement led to low simulation use in public secondary schools. This often results in passive or minimal use of simulations, thus limiting their pedagogical impact.

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2.6 Regional and Kenyan contexts of simulation integration

In Kenya, digital learning policies such as the Digital Literacy Programme and the Competency-Based Curriculum (CBC) emphasize the use of ICT in instruction (MoE, 2019). However, actual classroom integration, especially of PhET simulations, remains limited. A study by Abenga and Ogolla (2021) found that while science teachers in Kenyan urban schools showed moderate awareness of PhET, only a small proportion integrated simulations regularly—citing barriers such as lack of devices, power outages, and insufficient training.

Efforts by institutions like CEMASTEA and partnerships with international organizations have initiated ICT integration workshops, but these are often infrequent and inaccessible to teachers in rural public schools (Wanjiru et al., 2024). Mugo and Atieno (2023) emphasized that counties in Western Kenya lacked budgetary allocations for digital learning, leading to disparities in simulation implementation. Consequently, teacher engagement with simulations like PhET is sporadic, with minimal structured support for implementation fidelity.

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2.7 Gaps in the reviewed literature

While global research increasingly supports the value of PhET and other simulations in science education, few studies center on teacher engagement-most focus on student outcomes or software design (Perkins et al., 2021; Akpan et al., 2023). Even fewer explore the relational dynamics between teacher engagement, learner engagement, and conceptual understanding in rural, resource-limited settings like Kenya. Moreover, localized studies rarely examine how structured teacher involvement-before, during, and after simulation use—shapes learning outcomes. This study addresses these gaps by investigating how teacher engagement with PhET simulations in Kenyan public secondary schools affects learner engagement and conceptual understanding, and what contextual factors enable or hinder this process.

III. METHODOLOGY

3.1 Research Design

This study employed a convergent parallel mixed-methods design to comprehensively examine how teacher engagement with PhET Interactive Simulations influences learner engagement and conceptual understanding in science. The choice of design allowed for simultaneous collection and integration of both quantitative and qualitative data to provide a nuanced understanding of the phenomenon (Creswell & Plano Clark, 2018). Quantitative methods captured measurable changes in learner outcomes and engagement levels, while qualitative approaches explored the nature, depth, and context of teacher engagement practices and the enabling or inhibiting factors in implementation.

3.2 Study Location and Participants

The study was conducted in 6 selected rural public secondary schools in Bungoma and Kakamega counties in Western Kenya. These counties were selected due to their documented digital infrastructure challenges and prior limited exposure to simulation-based instruction. The schools were identified using purposive sampling, based on their accessibility, willingness to participate, and diversity in science teacher profiles. The target population included science teachers and Form Two students in these schools. A total of 24 science subject teachers who had basic ICT competence participated in the study. Each teacher's class of approximately 55 students participated, yielding a student sample size of about 1,320 learners.

3.3 Instruments for Data Collection

To address the research objectives, the study utilized the following instruments:

3.3.1 Teacher and Learner Questionnaires

Structured questionnaires were developed to collect both teacher and learner perspectives. The teacher questionnaire assessed the frequency and depth of PhET simulation use, self-reported digital pedagogical competence, and perceived challenges and enabling conditions for integration. Learners responded to items measuring their engagement during PhET-supported lessons, perceived clarity of concepts, and changes in motivation or interest in science following simulation use. All items were rated on Likert-type scales. The tools were validated through expert reviews from science education professionals and pilot-tested in two non-participating schools. Reliability was confirmed through Cronbach's alpha coefficients, which yielded acceptable internal consistency ($\alpha \geq 0.80$) for both instruments.

Structured questionnaires were administered to both teachers and learners. The teacher questionnaire measured:

i. Frequency and depth of engagement with PhET simulations
ii. Self-reported digital pedagogical competence
iii. Perceived barriers and enablers to simulation integration

The learner questionnaire captured:

i. Levels of engagement during lessons involving PhET
ii. Perceived clarity and understanding of scientific concepts
iii. Interest and motivation in science before and after exposure

Both questionnaires employed Likert-type scales and were validated through expert review and pilot testing. Internal consistency was assessed using Cronbach's alpha, yielding acceptable reliability coefficients ($\alpha \geq 0.80$).

3.3.2 Classroom Observation Checklist

To capture authentic classroom practices, a structured observation checklist was used during PhET-integrated science lessons. Observers documented teacher behaviors including modeling of simulation use, scaffolding techniques, and inquiry-based questioning strategies. Additionally, indicators of student engagement-such as hands-on interaction with simulations, participation in group discussions, and inquiry task completion-were recorded. Each participating teacher was observed over three lessons to ensure consistency and reliability. These observations offered a qualitative lens on teacher engagement and learner behaviors during simulation use.

A structured observation schedule was used to record teacher behaviors during PhET-integrated lessons. The checklist captured:

i. Teacher modeling and scaffolding techniques
ii. Use of pre-, during-, and post-simulation questioning
iii. Evidence of student participation, inquiry, and collaboration

Observations were conducted over three consecutive science lessons per teacher.

3.3.3 Pre- and Post-Test Assessments

To evaluate conceptual understanding, learners completed standardized pre- and post-tests aligned with the topic content covered using PhET simulations. The test items were drawn from the Kenya Institute of Curriculum Development (KICD) frameworks and evaluated application and conceptual mastery. Construct validity of the tests was ensured through expert review by curriculum specialists and pilot testing in a separate sample of learners not included in the study. Items were reviewed for alignment with intended learning outcomes and adjusted based on feedback.

3.3.4 Focus Group Discussions (FGDs)

To enrich the quantitative findings, focus group discussions were conducted with two sets of teachers (n=6 per group) purposively selected for diversity in experience and subject specialization. Discussions explored firsthand experiences using PhET in classroom settings, professional development needs, implementation challenges, and perceived learner impacts. The sessions were audio-recorded and transcribed verbatim for analysis. The FGDs allowed for the emergence of rich, contextual themes that complemented the structured data, providing a deeper understanding of the instructional realities and professional needs in simulation-enhanced science teaching.

Two focus group discussions were conducted with subsets of teachers (n=6 per group) to explore:

i. Experiences using PhET in real classrooms
ii. Challenges and professional support needed
iii. Perceived impact on learners' conceptual understanding and classroom behavior

FGDs were recorded and transcribed for analysis.

3.4 Data Collection Procedures

Data were collected over a 14-week school term. In week 1, pre-tests were administered and baseline teacher practices were observed. Weeks 2 to 10 involved implementation of PhET-enhanced lessons across selected science topics. During this period, lesson observations and mid-term interviews were conducted. Post-tests and final questionnaires were administered in week 11, and FGDs took place in week 12.

3.5 Data Analysis Techniques

3.5.1 Quantitative Data Analysis

Quantitative data from questionnaires and tests were analyzed using **SPSS version 25**. Descriptive statistics (means, standard deviations) were used to summarize engagement levels. Inferential statistics included:

i. Paired-sample t-tests to assess pre- and post-test differences in learner conceptual understanding
ii. Pearson correlation analysis to determine the relationship between teacher engagement and learner outcomes
iii. Regression analysis to evaluate predictors of learner engagement

3.5.2 Qualitative Data Analysis

Qualitative data from classroom observations and FGDs were analyzed thematically using NVivo software. Thematic coding followed Braun and Clarke’s (2006) six-step framework: familiarization, initial coding, theme generation, theme review, definition, and reporting. NVivo queries were used to code for themes such as 'teacher modeling', 'learner inquiry behavior', 'simulation accessibility', and 'barriers to implementation'. Triangulation of data sources ensured credibility and validity of findings.

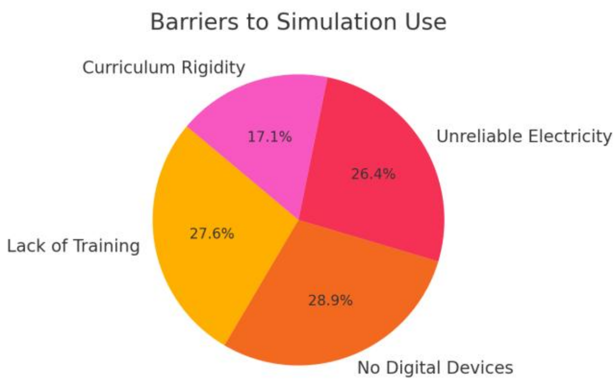
3.6 Ethical Considerations

Ethical clearance was obtained from the university’s research ethics committee. Permissions were secured from school administrations and County Directors of Education. Informed consent was obtained from teachers, and assent from learners, ensuring anonymity and voluntary participation. Data were securely stored and used strictly for research purposes.

IV. FINDINGS

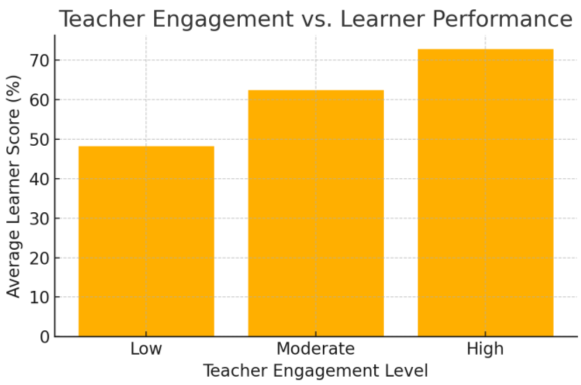
4.1 Objective 1: To assess the levels of teacher engagement with PhET Interactive Simulations in science classrooms

A survey of science teachers revealed that 63% use PhET simulations in at least three lessons per week. Despite this moderate engagement level, significant barriers exist: 68% of teachers cited lack of professional training, and 71% of schools reported unreliable electricity and insufficient access to digital devices. Observation data corroborated these findings, indicating that only 52% of teachers consistently modeled the use of simulations before student interaction, while 65% facilitated guided questioning during or after simulation use.



4.2 Objective 2: To determine the impact of teacher engagement with PhET on learner engagement

Observation and survey data showed that 77% of learners were actively engaged during PhET-supported lessons, with activities including manipulating simulations and participating in inquiry-based tasks. Additionally, 81% of students reported increased attention and interest during PhET-integrated instruction. Notably, classes where teachers provided structured facilitation and scaffolding exhibited higher levels of student collaboration and participation.



4.3 Objective 3: To evaluate the relationship between teacher engagement and learners' conceptual understanding in science

Learner performance data demonstrated a mean improvement of 28 percentage points between pre- and post-test assessments. Furthermore, 84% of learners self-reported improved conceptual clarity. Statistical analysis confirmed a moderate positive correlation ($r = .57$, $p < .01$) between the frequency of teacher engagement with simulations and learner test score gains. The ANOVA test yielded statistically significant results ($F = 524.65$, $p = 0.0000$), indicating the effectiveness of teacher-led PhET instruction.

4.4 Objective 4: To identify challenges and enablers in implementing PhET simulations in science instruction

Challenges Identified:

Limited access to digital devices (71%)
Unreliable electricity and internet connectivity
Inadequate professional development (68%)
Curriculum rigidity restricting integration of simulations

Enablers Identified:

Contextualized teacher training programs
Collaborative planning among teachers
Access to offline and localized PhET simulation tools

4.5 Summary of Key Quantitative Indicators

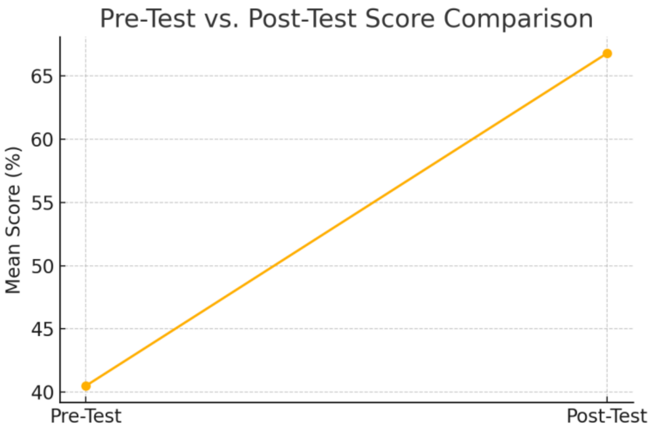
Indicator	Value (%)
Average increase in learner test scores	**28**
Teachers using PhET in ≥ 3 lessons per week	**63**
Learners reporting improved understanding	**84**
Learners actively engaged in PhET lessons	**77**
Teachers citing lack of training	**68**
Schools lacking digital infrastructure	**71**

Figure: Learners Reporting Improved Conceptual Understanding by Gender

Male: 47.3%
Female: 52.7%

Summary Interpretation:

Average Pre-Test Score: 40.5
Average Post-Test Score: 66.8
Mean Score Gain: 26.3 points



V. DISCUSSION

5.1 Teacher Engagement Levels and Practices

This study revealed that a majority (63%) of science teachers used PhET simulations in at least three lessons weekly, indicating moderate engagement. However, consistent modeling and guided questioning were less frequent. These findings align with Tondeur et al. (2018), who emphasize that technology integration depends on pedagogical competencies, not mere access. In the Kenyan context, Nyambura and Mburu (2021) observed similar patterns, underscoring the importance of continuous teacher support. Theoretical support from Vygotsky (1978) and the ICAP framework (Chi & Wylie, 2014) affirms that such teacher practices promote interactive and constructive learning engagement.

5.2 Impact of Teacher Engagement on Learner Engagement

The observation that 77% of learners were actively involved in PhET-supported lessons suggests strong learner engagement when teachers facilitate simulations effectively. Consistent with Akpan et al. (2023), teacher modeling significantly shapes student attitudes and participation. Wambugu and Githua (2019) similarly found that Kenyan learners taught with teacher-facilitated simulations demonstrated higher motivation and collaborative behaviors. Learner engagement was particularly pronounced in schools where teachers scaffolded inquiry tasks and used formative questioning.

5.3 Relationship Between Teacher Engagement and Conceptual Understanding

The study found a statistically significant correlation ($r = .57$, $p < .01$) between teacher simulation engagement and learner test gains. Learners in structured simulation-based instruction scored an average of 26.3 points higher post-intervention. These findings support Gupta and Pandey (2023) and Okereke et al. (2022), who reported similar gains. The use of simulation tasks aligned to KICD curriculum, validated through expert review and piloting, provided construct validity and instructional relevance.

5.4 Challenges and Enablers in Implementing Simulations

The study identified barriers including inadequate training (68%), limited infrastructure (71%), and curriculum rigidity. These echo findings from Mwarari and Mugambi (2021) and Otieno et al. (2023). Nonetheless, teachers highlighted enablers such as collaborative planning, access to offline simulations, and support from peers. CEMASTEA-led ICT workshops, though limited, were viewed as impactful (Wanjiru et al., 2024). Strategic interventions could help scale simulation use in rural and underserved schools.

5.5 Study Limitations and Areas for Further Research

This study was limited to selected rural schools in Western Kenya and focused on Form Two science classes. Results may not generalize to urban settings or other subjects. Additionally, engagement was measured over one school term, which may not reflect long-term trends. Future studies could explore longitudinal impacts of teacher simulation training, gender-differentiated engagement patterns, or simulation use in interdisciplinary STEM contexts.

VI. CONCLUSION

This study established that teacher engagement with PhET Interactive Simulations significantly influences both learner engagement and conceptual understanding in science education. While moderate levels of teacher engagement exist, barriers such as lack of training, digital resources, and rigid curricula limit full integration. Learners exposed to teacher-facilitated PhET instruction demonstrated higher engagement levels and significant learning gains. Addressing implementation barriers while reinforcing enablers can enhance the pedagogical value of simulations in under-resourced classrooms.

VII. RECOMMENDATIONS

The findings of this study have key implications for future teacher professional development and EdTech policy. First, simulation-based training should be embedded into pre-service and in-service teacher education to enhance pedagogical readiness for digital integration. Second, national education policies must promote access to offline and mobile-compatible simulation tools to bridge equity gaps in rural areas.

7.1 Short-term Actions: Training and Offline Access

i. Develop and deliver targeted, hands-on professional development programs that equip teachers with skills in integrating PhET simulations into science instruction.
ii. Provide downloadable, offline-compatible versions of simulations for schools with limited internet access.
iii. Establish local simulation champions or mentors to support teachers within clusters.

7.2 Medium-term Actions: Curriculum Review and Content Alignment

i. Revise curriculum support materials to explicitly recommend the use of simulations in science teaching and assessment.
ii. Integrate simulation-based tasks into formative and summative assessments to normalize their use in classroom practice.
iii. Encourage curriculum developers to align digital learning tools with the Competency-Based Curriculum (CBC) framework.

7.3 Long-term Actions: Policy Integration and Systemic Support

i. Institutionalize simulation use in national ICT in Education policies and strategic plans.
ii. Allocate specific budget lines for procurement of digital infrastructure and maintenance in rural schools.
iii. Partner with teacher training institutions and NGOs to co-create sustainable, context-sensitive models of simulation integration.

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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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