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Transforming STEM Education in Under-Resourced Contexts: A Conceptual Framework for AI-Supported OEP/Rs and Inquiry-Based Learning

Wiets Botes[1], Annie Kgosi[2], Simone Neethling[3], Lebohang Mahlo[4], Mpumelelo Faith Zondi[5]
[1,2,3,4,5]Faculty of Education, Sol Plaatje University, Kimberley, South Africa

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ABSTRACT
While digital innovation is rapidly transforming global classrooms, the pedagogical and resource divide in under-resourced STEM environments remains a critical barrier to equitable education. This conceptual paper aims to examine design-based practices (DBPs) for implementing Artificial Intelligence (AI)-supported Open Educational Resources and Practices (OEP/Rs) to promote inquiry-led teaching in STEM education within under-resourced contexts. Guided by the Inquiry-Based Learning (IBL) model, it explores how AI-supported digital simulations can be designed to enhance learner engagement and conceptual understanding. The methodology employs a critical and integrative literature review anchored in the 5E instructional framework to synthesize pedagogical benefits, implementation barriers, and design principles. The results present three adaptable teaching scenarios (natural science, technology, and mathematics) demonstrating how generative AI tools create curriculum-aligned, multilingual, and contextually relevant digital simulations. These findings show that AI-generated simulations successfully transform abstract concepts into interactive experiences, helping overcome infrastructural, linguistic, and contextual constraints in rural classrooms. The main contribution of this research lies in establishing a novel conceptual framework that bridges generative AI co-design with open pedagogy. It offers a scalable, cost-effective pathway for digital inclusion and equitable STEM education, providing actionable guidelines for educators to design localized digital learning objects without requiring advanced programming.

Keywords: Generative AI, Inquiry-Based Teaching, Interactive Digital Simulations, Lesson Design, STEM Education

Corresponding Author:
Wiets Botes
Faculty of Education, Sol Plaatje University, Kimberley, South Africa
Email: wiets.botes@spu.ac.za

1. INTRODUCTION

Even though Open Educational Practices and Resources (OEP/Rs) have gained popularity in science, mathematics and technology education globally, the use of interactive digital simulations as a type of OEP/R is still not fully realized (Menzli et al., 2022). OEPs extend beyond the mere use of resources to encompass participatory, collaborative and learner-centred approaches to knowledge construction (Laubscher et al., 2026), empowering self-directed learners through digital innovation and open educational practices. While OERs focus on the development and use of openly licensed materials that remove financial and legal barriers to access (van den Berg & du Plessis, 2023), their integration within mathematics education through tools such as GeoGebra exemplifies the potential to support dynamic, interactive learning through the visualisation of abstract concepts (Huang et al., 2026; Ziatdinov & Valles, 2022). Similarly, in science education, OEP/Rs have been shown to enhance learner engagement, promote inquiry-based learning and support multimodal representations of complex phenomena (Trust et al., 2023). One such example includes the use of PhET simulations, which enable learners to manipulate variables, test hypotheses and visualise abstract scientific processes in real time (Diab et al., 2024). These simulations support learners' conceptual understanding by providing interactive environments in which they can explore cause-and-effect relationships, thereby strengthening scientific reasoning and facilitating deeper engagement with the content. Beyond their pedagogical affordances, OERs play a critical role in improving access to quality educational resources, particularly in contexts where physical laboratory infrastructure and financial resources are limited (Otto & Kerres, 2022). However, despite these benefits, significant challenges persist. For example, in the South African context, where teaching and learning are guided by the Curriculum and Assessment Policy Statement (CAPS), many OERs are insufficiently aligned with prescribed curriculum requirements (Arispe & Hoye, 2023), limiting their usability and pedagogical effectiveness. Furthermore, existing OERs often fail to accommodate diverse learner needs and contextual realities, particularly in rural and under-resourced settings. These limitations highlight a critical gap between the potential of OEP/Rs and their practical implementation in contextually responsive ways.

To date, existing literature has predominantly examined static OER platforms or generic AI applications in isolation, leaving a distinct scholarship void regarding how generative AI can act as a pedagogical co-designer to build localized, curriculum-aligned STEM simulations for under-resourced schools. Addressing this challenge, the emergence of generative artificial intelligence (AI) presents a transformative opportunity to address these challenges. AI-enabled tools can design and generate customised, interactive digital simulations that are responsive to specific curriculum requirements, learner profiles and teaching contexts (Admane et al., 2024). This adaptability positions AI as a key enabler in advancing contextually relevant OEP/Rs that support both equity and inclusion in education. Against this backdrop, this paper seeks to contribute to the scholarship by exploring design-based practices for implementing AI-supported OEP/Rs in the teaching of inquiry-led science, mathematics and technology education. With this aim in mind, the study will be guided by two secondary research questions. In the first instance, it is essential to clarify the pedagogical benefits of digitisation in the teaching of science, mathematics and technology education. These pedagogical benefits will serve as a preamble to establish a theoretical and pedagogical foundation for understanding how digital tools, particularly interactive simulations, can enhance inquiry-based teaching and learning practices. Thereafter, an attempt is made to showcase how AI-supported OEP/Rs can be introduced to stimulate an inquiry-led teaching approach in subjects such as mathematics, science and technology. Given this focus, the paper advocates for a shift towards more adaptable, inclusive and inquiry-focused learning environments that improve both learner engagement and conceptual understanding. In the next section, an effort is made to clarify Inquiry-Based Learning, which will act as the conceptual foundation of the study.

1.2. The Inquiry-Based Learning (IBL) Model as a Conceptual Lens

To systematically anchor the proposed AI-supported digital simulations within a rigorous instructional framework, this study adopts the Inquiry-Based Learning (IBL) model as its primary theoretical lens. Inquiry-based learning, initially coined by Rodger Bybee is widely considered as a pedagogical approach in the context of science, mathematics and technology education that positions learners as active participants in the construction of knowledge through questioning, exploration, investigation and reflection (Kotsis et al., 2025). In following the IBL approach, learners engaged in teaching and learning practices that mirror authentic scientific practices associated with the scientific method. These practices included hypothesising, experimenting, analysing and interpreting data and drawing evidence-based conclusions. IBL is grounded in typical constructivist learning principles, which assert that knowledge is actively constructed through learner interaction with the classroom environment and social engagement (Morris, 2025). In the context of science, mathematics and technology education, the IBL model is particularly valuable as it promotes deeper conceptual understanding and mastery of complex scientific topics while developing learners' scientific process skills (Arifin et al., 2025). It is widely reported that inquiry-based teaching significantly enhances learners' ability to reason scientifically, engage critically with content, and retain knowledge over time (Gomez, 2025; Sam, 2024). A commonly adopted teaching model within the constructs of IBL is the 5E model, which structures learning into five phases: engagement, exploration, explanation, and evaluation (Abebe et al., 2025; Nzomo et al., 2023; Pei, 2025). The engagement phase is intended to activate learners' prior knowledge and stimulate curiosity, while the exploration phase allows learners to investigate concepts through hands-on or simulated educational experiences. The explanation phase, on the other hand, requires learners to articulate their understanding of the concept with the teacher as the facilitator, while the elaboration phase extends learning through application to new contexts. Finally, the evaluation phase assesses learners' conceptual understanding of topics and process skills. This structured yet flexible learning model has the potential to serve as a framework for integrating interactive digital simulations in science, mathematics and technology education.

In the context of this study, AI-supported OEP/Rs, such as interactive digital simulations, are conceptualised as powerful educational tools with the potential to operationalise the principles of IBL. These interactive digital simulations create opportunities for learners to manipulate variables, test hypotheses and observe real-time outcomes, thereby engaging learning in authentic scientific inquiry. As a result, learners construct their own knowledge through dynamic interaction with the visual and data-driven representations of scientific phenomena. Furthermore, the integration of generative AI enhances the potential of IBL by enabling science, mathematics, and technology educators to design customised simulations through prompt entries aligned with the specific curriculum requirements outlined in the South African CAPS, which governs teaching and learning practices. This is particularly important in rural and under-resourced teaching contexts where access to laboratory equipment is limited. Crucially, while traditional software development poses severe technical barriers for rural educators, generative AI lowers these technical thresholds, allowing teachers to bypass complex programming and directly co-create functional digital artifacts. It should be noted that AI-generated interactive simulations not only serve as powerful instructional tools but also enable equitable access to inquiry-based learning in science, mathematics, and technology.

2. METHOD

This study adopts an integrative review and design-based instructional modeling framework within a conceptual research design (Abuhassna et al., 2024). Unlike empirical studies that rely on primary data collection from physical classrooms, this conceptual paper synthesizes theoretical and empirical scholarship with systematic instructional design modeling to address pedagogical gaps in resource-constrained STEM education. By abandoning primary empirical data collection, the methodology focuses on generating replicable, design-based principles for implementing Artificial Intelligence (AI)-supported Open Educational Resources and Practices (OEP/Rs).

The operational framework is executed through a rigorous three-stage process involving integrative literature synthesis, theoretical translation of learning models, and instructional artifact development. The baseline parameters of this research are established through a systematic and integrative literature synthesis protocol. To ensure maximum academic validity, literature retrieval was confined to leading international indexing databases, specifically Scopus and Web of Science. A targeted keyword matrix was deployed utilizing boolean operators, which included the combination of terms such as "Generative AI" OR "Artificial Intelligence" AND "Open Educational Resources" OR "OEP" AND "Inquiry-Based Learning" OR "5E Model" AND "STEM Education" OR "Simulations". The extracted scholarship was filtered using a strict qualitative inclusion criterion, where articles were selected only if they explicitly addressed the pedagogical affordances of digital simulations, the conceptual expansion of resources into participatory practices, or the strategic use of AI to mitigate infrastructural and material barriers in under-resourced learning environments.

To ensure pedagogical rigor and prevent arbitrary design choices, the Inquiry-Based Learning (IBL) model serves as the primary theoretical anchor and analytical lens guiding the study. Specifically, the methodology operationalizes the classic 5E Instructional Model, which comprises engagement, exploration, explanation, elaboration, and evaluation (Polanin et al., 2024). This framework is applied systematically to evaluate how interactive digital simulations can successfully shift conventional teacher-centered routines into student-centered, data-driven inquiry environments. The analytical task focuses on formalizing how learners interact with digital learning objects to actively predict, experiment, manipulate variables, and analyze data within structured lesson phases.

To treat generative AI as a formal and rigorous methodological instrument, the creation of the instructional scenarios follows a strict three-step prompt engineering protocol. This protocol moves from system persona definition to pedagogical parameter constraint input, and concludes with an iterative optimization loop. The prompting structure mandates specific roles, such as instructing the AI to act as an expert pedagogical co-designer, defining target age demographics between 12 and 14 years, and setting technical deployment boundaries. These technical boundaries require the generation of single-file HTML scripts to ensure zero-installation, offline compatibility in rural settings where internet access is unstable. Furthermore, the protocol incorporates explicit pedagogical features into the prompt constraints, including dual-language toggles to support both English and Setswana instruction.

The technological feasibility, curriculum compliance, and localized adaptability of the proposed framework are validated through a dedicated curriculum cross-mapping matrix. Each developed instructional scenario underwent a comprehensive situational analysis evaluating available internal and external resources, classroom environmental layouts, and differentiated learning styles covering auditory, visual, and kinesthetic modalities. These parameters were cross-mapped with the performance indicators of the South African Curriculum and Assessment Policy Statement (CAPS) to guarantee strict lesson alignment between instructional objectives, simulation prompt constraints, and formative assessment questions. The structural configuration of these developed scenarios, their technical parameters, and their alignment with the validation matrix are systematized in the Table 1 below.

Table 1. Structural Configuration, Technical Parameters, and Validation Matrix of the Developed STEM Scenarios

Scenario and Subject	Core Pedagogical Concept and 5E Alignment	AI and Dynamic Tool Prompt Protocol	CAPS Mapping and Validation Matrix
Scenario 1: Natural Science (Grade 8)	Modelling exponential bacterial growth over time to shift learners from passive listening to active data-driven inquiry.	Human-AI collaborative co-design loop utilizing single-file HTML code generated via iterative ChatGPT prompting with an embedded English and Setswana language toggle.	Cross-mapped with Grade 8 microbial characteristics; validated against auditory, visual, and kinesthetics. learning styles via interactive petri dish grids, live graph updates, and verbal reflections.
Scenario 2: Technology Education	Simulating mechanical and hydraulic systems to demonstrate fluid incompressibility, Pascal's principle, and force transmission.	Collaborative multi-AI workflow using ChatGPT for structural prompt synthesis and Claude-AI for functional, error-free executable code displaying driver and driven syringes.	Aligned with CAPS mechanical systems and controls; validated via real-time calculations of mechanical advantage, volume displacement, and interactive plunger manipulation.
Scenario 3: Mathematics Education	Dynamic geometry simulation of a line of symmetry to transform abstract geometric reflections into tangible spatial experiences.	Integration of the dynamic Computer Algebra System (CAS) and intelligent feedback features within the GeoGebra software environment.	Positioned within the CAPS Geometry strand; validated by tracing a symmetrical biological leaf and using automated tools to measure equidistant points from the axis of reflection.

3. RESULTS AND DISCUSSION

3.1. The Pedagogical Benefits of Digitisation in the Teaching of Science, Mathematics and Technology Education

To address the first research question, the synthesis of literature reveals that the integration of digital technologies significantly enhances the quality of basic education on a global scale (Mhlongo et al., 2023; Timotheou et al., 2023). Within the spectrum of emerging technologies, which includes augmented reality, virtual reality, artificial intelligence, and hands-on modeling, immersive digital simulations serve as the primary focus of this paper. These simulations establish interactive learning environments that replicate scientific phenomena, processes, and experiments within a virtual space, thereby fostering a deep and engaging learning experience through realistic and multisensory interactions (Tene et al., 2024). This pedagogical affordance is visible across various immersive architectures, including three-dimensional visualizations such as virtual models of cells, ecosystems, or chemical reactions (Botes, 2025; Mahlo & Waghid, 2023), virtual reality applications like virtual field trips or virtual laboratories (Salman, 2023), and scenario-based simulations centered on problem-solving and critical thinking (Guler, 2025).

In the context of STEM education, immersive digital simulations are exceptionally valuable for simplifying complex concepts and creating accessible learning pathways (Baxter & Hainey, 2024). Comparative scholarship demonstrates that learners engaging with open-source digital simulations experience a significant increase in conceptual comprehension compared to traditional, teacher-centered instructional delivery methods (Porat et al., 2023; Zabasta et al., 2024). Rather than promoting passive consumption, digital simulations foster active learning by enabling students to experiment with and explore diverse scientific scenarios. Crucially, the systemic accessibility of these open digital assets implies that STEM educators from constrained backgrounds can adopt advanced teaching methodologies without relying on expensive physical infrastructures. This democratization of digital tools serves as a critical lever for promoting inclusion in under-resourced areas, ultimately enabling marginalized learners to successfully pursue scientific disciplines and career trajectories.

Extant literature confirms that immersive digital simulations generate substantial pedagogical benefits by creating interactive scenarios that challenge learners to explore abstract concepts beyond the limitations of traditional classrooms (Negahban, 2024; Serrano-Ausejo & Mårell-Olsson, 2024). For instance, virtual lab environments allow students to safely conduct hazardous or logistically impossible experiments, such as mixing dangerous chemical compounds or evaluating the environmental impacts of oil spills (Hou et al., 2023). Furthermore, these simulated environments can transport learners across diverse ecosystems, enabling real-time observation of complex ecological interactions, biodiversity patterns, and conservation efforts. This active approach strengthens conceptual understanding through hands-on, authentic activities that stimulate deep cognitive engagement (Nualjan & Panjaburee, 2025; Tene et al., 2024). Consequently, immersive simulations function as vital operational spaces for inquiry-based learning, encouraging students to test hypotheses, investigate spontaneous ideas, observe systemic changes, and actively construct scientific knowledge rather than passively receiving information from the educator.

3.2. Design-Based Practices for Implementing AI-supported OEP/Rs in the Teaching of Inquiry-Led Science, Mathematics and Technology Education

The successful integration of digital simulations requires a deliberate, structurally planned, and pedagogically sound approach that aligns inquiry-based learning with specific teaching contexts and instructional objectives. Educators must first execute a situational analysis to assess both internal and external factors influencing the learning environment (Aulia et al., 2025). This diagnostic process involves evaluating physical and digital resources (such as hardware availability, textbooks, and network stability), accounting for diverse learning styles (including visual, kinesthetic, and auditory modalities), and managing environmental constraints such as classroom layouts and structural time limits. Following this situational analysis, instructional objectives must be formulated around problem-solving frameworks before digital simulations are embedded into the lesson architecture. Grounding these objectives requires an operational understanding of inquiry-based principles, specifically the activation of prior knowledge, immersive exploration, student-driven explanation, conceptual elaboration through practical application, and systematic evaluation. These sequential components form the core of the 5E instructional model (Abebe et al., 2025; Morris, 2025). Utilizing this framework allows teachers to construct highly engaging introductions that evaluate prior understanding while structuring core classroom activities, whether utilizing direct instruction, cooperative groups, or independent task rotations, around active student participation. Maintaining construct alignment dictates that learning objectives, real-time activities, and formative assessments remain mutually supportive, culminating in structured opportunities for learner reflection.

Once the instructional plan is established, educators can integrate digital simulations sourced from open platforms (such as GeoGebra, PhET, or Lab Exchange) or custom-developed via generative tools like ChatGPT and Claude AI. Within STEM pedagogy, these simulations must prompt active inquiry behaviors, including asking targeted questions, formulating hypotheses, manipulating environmental variables, and interpreting automated data streams. This application is evident in virtual experiments that allow students to analyze complex processes, such as chemical reactions or cellular synthesis, safely and repeatedly within controlled spaces. As emphasized by Singh-Pillay (2024), technology integration must avoid treating digital tools as standalone activities, ensuring they serve to reinforce core conceptual connections instead. In this capacity, the teacher functions as a facilitator who scaffolds cognitive engagement by delivering targeted prompts, guiding reflective periods, and encouraging students to articulate their scientific reasoning. This intentional design framework transforms abstract curriculum concepts into tangible, interactive experiences that strengthen critical thinking skills across diverse teaching contexts.

3.2.1. Teaching Scenario 1: Simulating Bacterial Growth over a Period of Time

The first scenario demonstrates the instruction of microbial characteristics and reproductive processes within the Grade 8 Natural Science curriculum, utilizing an integrated mix of direct instruction, structured discussion, and targeted questioning. This scenario incorporates generative AI platforms to construct an interactive digital workspace designed to evaluate higher-order scientific reasoning. The baseline lesson architecture focuses on ensuring that learners comprehend the physical classification, structural features, and binary fission mechanisms characteristic of bacterial populations.

3.2.1.1. Creating the Digital Simulation

To accommodate differentiated learning styles across auditory, visual, and kinesthetic modalities, a customized digital learning object was co-designed via a structured prompt interaction with ChatGPT. The prompt instructed the model to develop a complete Bacterial Growth Explorer simulation using single-file HTML code, incorporating parameters for exponential growth curves, interactive colored bacteria indicators, hover-triggered informational tooltips, an automated CSV data export utility, and a horizontal data grid tailored for a young demographic. The standalone HTML file architecture guarantees full offline functionality, making the tool suitable for deployment in infrastructures with unstable internet access. In this development loop, generative AI serves as an active pedagogical co-designer that accelerates the construction of specialized software tools (Anderson et al., 2025; Li et al., 2025). This human-AI collaboration enables educators to iteratively refine code prompt strings until the output fully complies with state curriculum guidelines, features local language variations, and effectively visualizes microscopic processes. Consequently, this process democratizes software creation, allowing teachers without advanced computer programming backgrounds to deploy highly interactive simulations in resource-constrained classrooms.

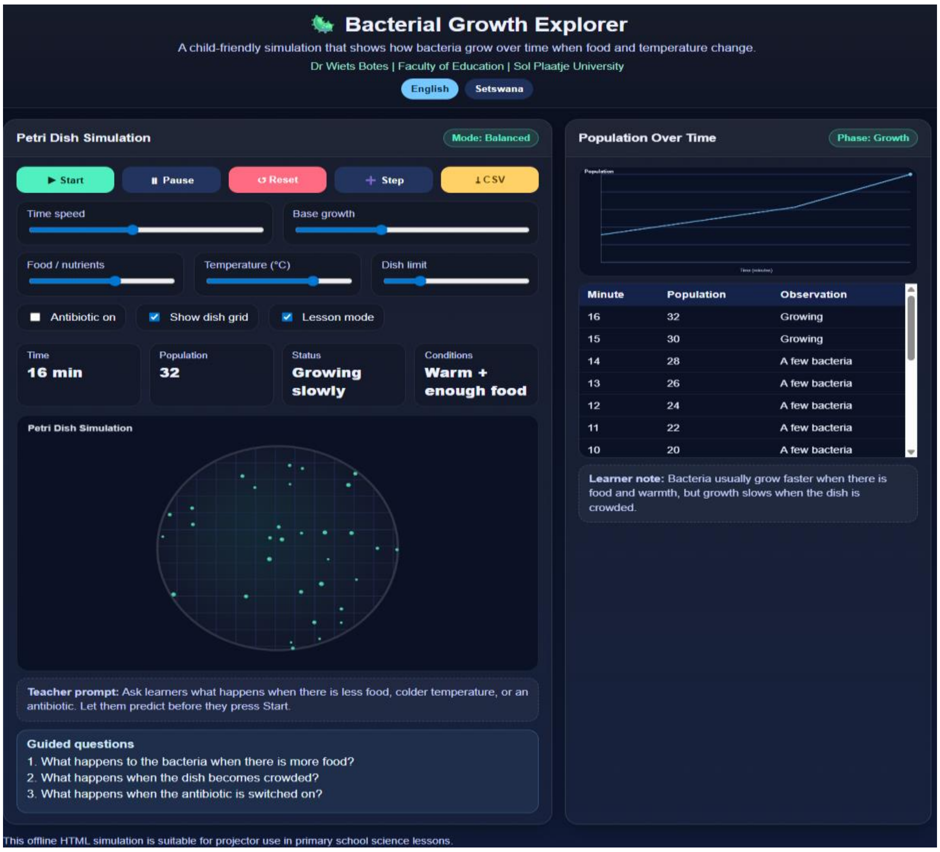

Figure 1. An Interactive Simulation Designed to Test Learners' Understanding of Concepts Related to Bacterial Growth

Examining Figure 1 more closely, we see an interactive simulation intended for multilingual users, supporting both English and Setswana. This enhances the learning experience by enabling learners to interact with the content in their preferred language and fostering a more inclusive educational setting. When the Setswana interface is activated, the screenshot below illustrates the simulation's multilingual nature.

Figure 2. A Setswana Rendition of the Bacterial Growth Simulation

Besides its multilingual features, the simulation offers learners a hands-on way to see and control exponential growth instead of just listening about it. As in Figure 2, by changing the initial population, growth factor, and speed, learners can instantly see how the coloured bacterial dots multiply in the "petri dish," while a graph and data table update live. This visualization helps them link the micro-level (individual dots or bacteria) with the macro-level (overall population trend). The English/Setswana toggle promotes multilingual learning and inclusion, enabling learners to understand the same scientific concept in their native language, which enhances both their conceptual grasp and scientific literacy.

3.2.1.2. Benefits of the Simulation Linked to Inquiry-Based Learning

The deployment of the Bacterial Growth Explorer simulation allows for the operational mapping of key science process skills. The primary instructional goals focus on ensuring that students can describe microbial morphology, analyze live data grids to identify distinctive population phases (including lag, exponential, stationary, and decline phases), and establish causal connections regarding how environmental variables alter reproduction rates. Through direct interaction with the user interface, learners actively construct and evaluate scientific hypotheses by manipulating isolated variables such as nutrient levels, temperature points, and pH values.

This interactive framework is integrated directly into a structured lesson plan that balances direct instruction with student-led discovery. The lesson opens with an engaging real-world prompt regarding seasonal food spoilage rates to evaluate prior student conceptions. Following this introduction, the teacher utilizes direct instruction to build foundational knowledge regarding bacterial taxonomy and growth requirements, linking these concepts to ecological and medical contexts such as fermentation and disease transmission. The lesson then transitions into an active inquiry session where students utilize the digital simulation to test context-specific predictions, such as comparing bacterial proliferation on food items left exposed to heat versus those placed inside cold storage. By modifying temperature sliders and tracking live graphical updates, students compare their initial predictions with empirical digital evidence. The instructional sequence concludes with a structured debriefing period where formative evaluation questions are deployed to assess conceptual mastery of microbial biology.

3.2.2. Teaching Scenario 2: Simulating Hydraulic Systems in the Subject Technology

The second scenario targets the mechanical systems and controls module within the Technology curriculum, concentrating specifically on fluid power mechanics. Traditional tactile approaches often rely on manual syringe experiments where two fluid-filled cylinders of varying volumes are linked via plastic tubing to demonstrate Pascal's principle. This mechanical setup illustrates force transmission, showing that pressure applied to an enclosed, incompressible liquid transfers equally throughout the system. Pushing a smaller input cylinder serves to multiply the output force, thereby generating a mechanical advantage greater than one, while resulting in a smaller extension distance due to volume displacement rules. Conversely, reversing the input to the larger cylinder divides the output force while increasing total linear extension. This scenario translates these mechanical concepts into a highly responsive digital simulation co-created through an automated multi-platform AI workflow.

3.2.2.1. Creating the Digital Simulation

The digital artifact was generated by utilizing ChatGPT to author optimized system prompts, which were subsequently executed within Claude AI to produce a functional simulation interface. The design constraints required an interactive visualization of fluid incompressibility, real-time calculations of mechanical advantage ratios, and clear indicators of cylinder surface areas. The resulting interface, illustrated in Figure 3, models Pascal's law by dynamically altering the output plunger position in response to user input on the primary driver plunger. Students manipulate mechanical advantage variations by modifying the volumetric properties of both the input and output cylinders. Selecting a larger output cylinder displays an increase in total force alongside a proportional reduction in extension distance, whereas selecting a smaller output profile exhibits extended distance parameters with diminished mechanical force. The fluid mechanics are reinforced via synchronized fluid visualizations that demonstrate how incompressible liquids transmit work across closed systems. Interacting with these diverse layout options enables students to systematically unpack the mechanical trade-offs between force multiplication and displacement distance that dictate the design of industrial applications such as automotive braking systems and heavy excavation equipment.

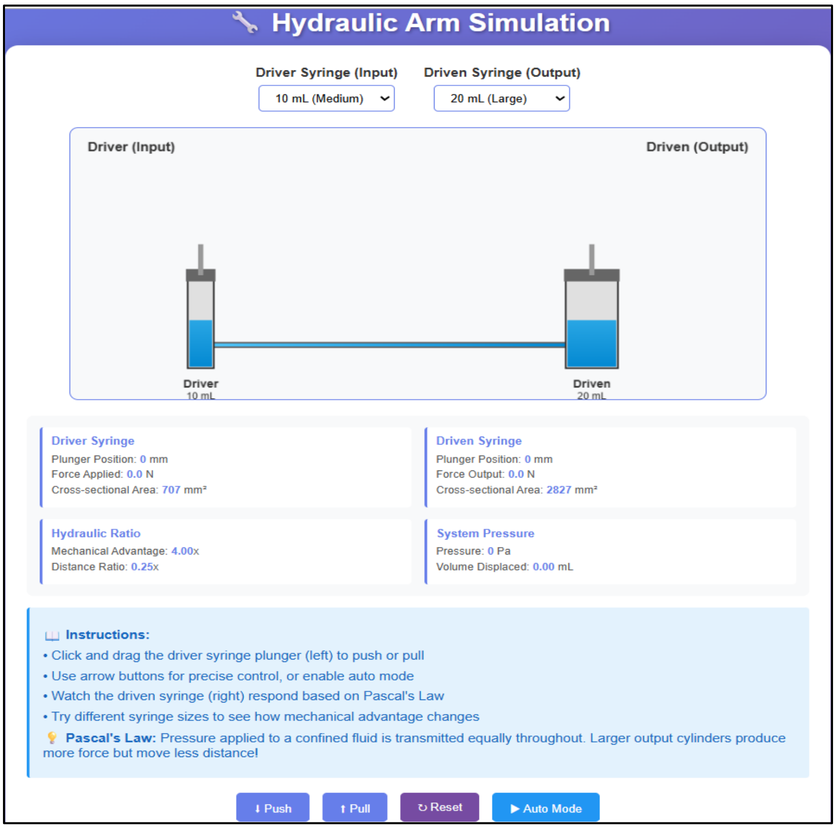

Figure 3. The Interactive Hydraulic Arm Simulation Interface Generated via a Claude-AI Cooperative Design Workflow

3.2.2.2. Benefits of the Simulation Linked to Inquiry-Based Learning

This digital simulation enhances engagement by allowing students to manually control input plungers, effectively converting abstract fluid principles into direct cause-and-effect observations. Acting as an instructional facilitator, the educator coordinates these interactions to build an inquiry-driven environment. Methodological literature indicates that systematic inquiry-based models yield significantly higher learning gains in science and technology contexts compared to conventional passive instruction (Arifin et al., 2025). The software architecture provides instantaneous visual feedback via synchronized fluid animations, moving mechanical parts, and automated computational metrics that display immediate changes in force, interior system pressure, and directional distance. This responsive design satisfies critical cognitive parameters, as immediate instructional feedback allows students to adjust their conceptual frameworks in real time, thereby preventing structural misconceptions regarding mechanical systems from becoming established (Kunnath & Botes, 2025). The capacity to execute unconstrained experimentation by modifying cylinder volumes encourages independent discovery, allowing students to deducively determine the engineering rationale behind heavy machinery layouts and the performance impacts of inverted mechanical systems.

3.2.3. Teaching Scenario 3: Simulating a Line of Symmetry by Tracing the Features of a Symmetrical Leaf

The third scenario investigates the instructional affordances of GeoGebra, an integrated platform that pairs Dynamic Geometry Software (DGS) with Computer Algebra Systems (CAS), to improve student comprehension of line symmetry by tracing the physical parameters of a symmetrical biological leaf. Geometric symmetry concepts are frequently perceived as highly abstract abstractions by learners when instruction lacks physical or digital manipulatives. Within state curriculum guidelines, line symmetry serves as a critical foundational pillar within the Space and Shape instructional strand, designed to cultivate structural visual reasoning and spatial coordination across multiple levels of complexity. By enabling the dynamic visualization of mathematical relationships, GeoGebra allows students to evaluate geometric conjectures and execute exploratory tasks that bypass the cognitive limitations of static textbook diagrams (Gurmu et al., 2024; Kgosi, 2025; Ziatdinov & Valles, 2022). Utilizing GeoGebra as an instructional mediator within resource-limited math classrooms directly highlights broader considerations regarding digital equity, inclusion, and pedagogical modernization. This design invites an evaluation of how open digital environments support cognitive growth in under-resourced schools, illustrating how classroom practitioners can balance technological innovations with infrastructural constraints to generate meaningful mathematics instruction.

3.2.3.1. Creating the Digital Simulation

Geometric reflection principles are operationalized within GeoGebra by giving students a fluid workspace to investigate lines of symmetry through real-time manipulation. In contrast to text-based generative large language models, GeoGebra integrates embedded algorithmic intelligence that assists students via automated construction rules, geometric suggestions, and immediate error checking during object manipulation (Eti et al., 2026; Kuncoro et al., 2026). The platform command console and integrated algebra engines parse natural mathematical notation to predict user commands, generating adaptive feedback loops that help students correct structural mistakes and evaluate alternative analytical approaches. This functionality allows students to manipulate objects symbolically rather than relying solely on numerical estimations or static coordinates (Kgosi, 2025), giving the computational engine the capacity to process exact algebraic equations. Consequently, the system can expand expressions, resolve geometric values symbolically, and track functional changes, allowing students to identify the mathematical structures governing visual reflections.

3.2.3.2. Benefits of the Simulation Linked to Inquiry-Based Learning

These interactive elements facilitate exploratory tasks by scaffolding student work without replacing necessary mathematical justification. For instance, students can generate a base polygon and employ the reflection utility to evaluate whether a user-defined axis generates perfectly congruent halves, receiving immediate visual proof regarding symmetry accuracy. By modifying vertices dynamically, students observe how reflective orientations and total lines of symmetry shift instantly, a process that improves spatial understanding far better than paper-based instruction. As illustrated in Figure 4, educators can direct students to establish alternative horizontal or vertical reflection axes across diverse shapes, such as regular polygons or circular curves, to systematically analyze why certain figures accommodate infinite lines of symmetry while irregular variations accommodate none.

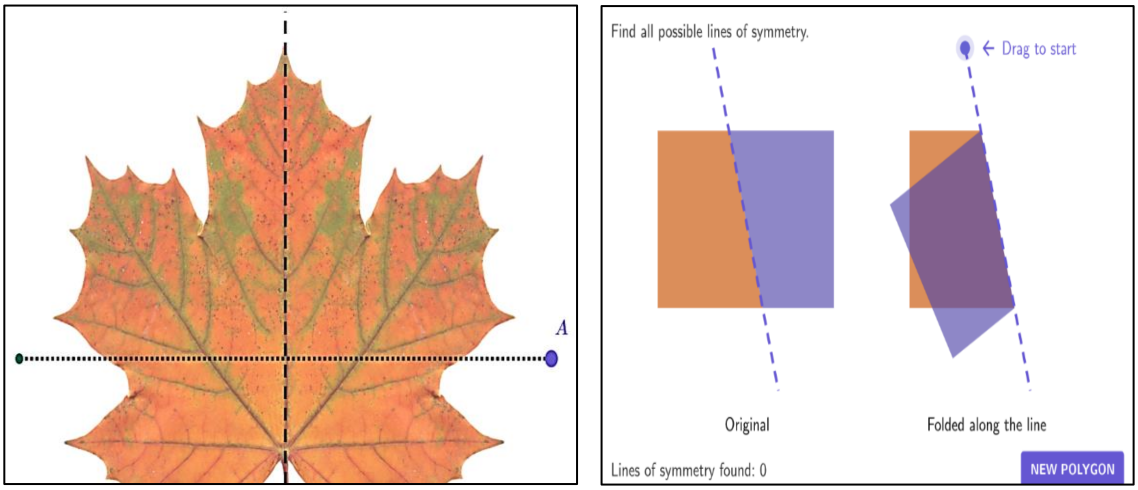

Figure 4. Simulating a Line of Symmetry by Tracing the Features of a Symmetrical Leaf

A closer look at Figure 4 reveals that GeoGebra enables learners to measure distances of corresponding points from the line of symmetry, reinforcing the idea that symmetry is a reflection where points are equidistant from the line. Through these explorations, GeoGebra supports CAPS-aligned learning by promoting visual reasoning, experimentation, and mathematical justification rather than rote identification.

3.3. Discussion of Teaching Scenarios

All three teaching simulations presented in this conceptual paper illustrate how immersive digital simulations developed with generative AI tools, mainly ChatGPT and Claude AI, can be meaningfully integrated into STEM lessons to deepen learners' conceptual understanding and scientific reasoning. In line with the literature presented within the preceding theoretical frameworks, the scenarios demonstrate how digitalisation in science education can shift conventional teacher-centred practices toward more inquiry-oriented, learner-centred pedagogies, even in resource-constrained rural environments. To begin with, all three instructional designs deliberately used engaging and contextually appropriate introductions, allowing educators to activate learners' prior knowledge, a key feature of inquiry-based learning (IBL). As emphasised by Baxter & Hainey (2024), introducing scientific concepts through relatable scenarios increases situational interest and prepares learners for cognitive engagement. For instance, relating bacterial growth to food spoilage enabled learners to make meaningful links between scientific content and everyday experiences. Transitioning into the main teaching episodes, each scenario purposefully employed direct instruction to establish foundational disciplinary knowledge. This echoes Wahidin et al's. (2025) observation that digital simulations are most effective when learners possess a baseline conceptual understanding before engaging in exploratory scientific inquiry. At this stage of the lesson, learners acted as receptive participants, a necessary scaffolding step to ensure that subsequent engagement with the digital simulations was conceptually grounded. After this foundational phase, the lessons shifted to student-focused, inquiry-based methods, aligning with the principle formulated by Sun et al. (2022) that simulations must function as integral components of a broader inquiry process rather than operating in isolation. The integration of these interactive interfaces operationalizes the classic 5E instructional framework, facilitating a structured transition through engagement, exploration, explanation, elaboration, and evaluation. This architectural alignment complies with the broader scholarship on the pedagogical affordances of digital learning objects, specifically their capacity to strengthen conceptual comprehension, accommodate multimodal learning pathways, and reinforce core scientific process skills including hypothesising, variable manipulation, data interpretation, and evidence-based argumentation (Tene et al., 2024).

In Scenario 1, the bacterial growth simulation operationalizes these principles by allowing learners to visually track exponential population metrics, manipulate hidden environmental constraints, and interpret live graphical charts, thereby directly stimulating advanced science process skills. Furthermore, this intervention supports multimodal and visual processing preferences, addressing the diverse learning profiles established during the initial situational diagnostic phase. These activities exemplify the parameters of digital science inquiry, where students systematically construct knowledge through targeted interactions with responsive visual models. A critical asset of Scenario 1 is its commitment to inclusive, multilingual digital learning, featuring user interfaces that support both English and Setswana instruction. This design responds directly to the pedagogical critique raised by Khair & Sukumaran (2025) regarding the pervasive lack of contextual and linguistic responsiveness in generic OER landscapes. Conversely, deploying localized digital assets enables culturally responsive adaptations that minimize cognitive barriers and secure equitable academic participation within under-resourced rural classrooms.

Similarly, the fluid power simulation in Scenario 2 establishes rigorous pathways for inquiry-driven technology education. By adjusting digital plunger positions and evaluating varied cylinder volume configurations, learners mimic authentic engineering inquiries, systematically testing hypotheses regarding how modifications in mechanical surface areas and directional displacement dictate internal pressure levels, force output, and total mechanical advantage ratios. This operational matrix aligns with the Explore and Explain phases of the 5E framework, forcing students to analyze the underlying cause-and-effect mechanics linking input and output vectors. The synchronized fluid animation, paired with instantaneous computational metrics, assists students in connecting macro-level industrial applications (such as automotive brakes or excavation machinery) with micro-level physics principles governing pressure distribution in incompressible media. As confirmed by contemporary scholarship, such rich multimodal representations are essential for guiding students through the internal structures of abstract scientific concepts (Tene et al., 2024).

In Scenario 3, the GeoGebra workspace extends this conceptual framework into the domain of dynamic mathematical exploration. By giving students the capacity to construct, modify, and reflect geometric properties interactively, the platform reinforces the Explore and Explain components of the 5E architecture. Students evaluate geometric conjectures regarding lines of symmetry by analyzing instantaneous transformations as they reposition polygon vertices and reflective axes, thereby activating mathematical reasoning skills and direct visual verification behaviors. This application complies with foundational research indicating that dynamic geometric software architectures strengthen conceptual mastery by allowing students to explore the fluid relationships governing mathematical objects rather than restricting them to static textbook layouts. Additionally, the simulation cultivates spatial reasoning and visual literacy, which represent core competencies required within the geometry curriculum framework. As students calculate linear distances and evaluate congruence criteria across reflected shapes, they formulate geometric justifications using data derived directly from the digital environment, thereby anchoring rigorous inquiry practices. Consequently, Scenario 3 illustrates that AI-supported open pedagogy can successfully expand beyond natural sciences to transform abstract mathematical relationships into tangible, accessible learning objects.

Finally, all three instructional tracks encourage collaborative interaction through cooperative peer debates, partner tasks, and structured whole-class synthesis sessions. This implementation reflects social constructivist learning paradigms, which assert that conceptual knowledge is constructed through interpersonal discourse and shared cognitive negotiation (Botes & Philip, 2025). As observed by Park et al. (2025) and Harrison (2025), open educational practices inherently catalyze participatory and collaborative learning environments, and these simulations prove that adaptable digital instruments significantly enrich classroom dialogue and collective comprehension. Furthermore, each instructional sequence incorporates specific pathways for metacognitive processing and self-directed learning, achieved via structured inquiry worksheets where students log initial predictions, coordinate software variables, record empirical observations, and draft analytical conclusions. This reflective methodology reinforces inquiry-led instruction, assisting students in developing the capacity to monitor, evaluate, and calibrate their own conceptual frameworks, which remains a fundamental requirement for comprehensive scientific literacy.

4. CONCLUSION

This research establishes a comprehensive design-based framework for implementing Artificial Intelligence (AI)-supported Open Educational Resources and Practices (OEP/Rs) within inquiry-led STEM education, specifically tailored to meet curriculum requirements in rural and under-resourced learning environments. By operationalizing the Inquiry-Based Learning (IBL) model, the study demonstrates that AI-supported open pedagogy serves as a vital digital intervention to deepen conceptual comprehension, support multimodal representation, and enable variable manipulation that is structurally difficult to replicate in conventional classrooms. Concurrently, systemic challenges such as restricted teacher preparedness, infrastructural deficits, curriculum misalignment, and a scarcity of localized learning assets remain significant barriers to sustainable deployment. Notwithstanding these limitations, the integration of generative AI within open pedagogy offers a scalable mechanism, empowering educators to co-design contextually relevant, syllabus-aligned simulations that systematically expand educational access, classroom participation, and digital inclusion.

In addressing the primary research questions, the developed instructional scenarios indicate that interactive digital learning objects allow learners to effectively visualize abstract concepts, coordinate independent variables, and analyze live empirical data streams. This digital capacity directly transcends the material boundaries of traditional, under-resourced laboratory experiments. Mechanistically, tracking exponential biological reproduction, manipulating fluid transmission parameters, and dynamically adjusting geometric vertices collectively illustrate how digital transformations convert theoretical constructs into interactive, empirical realities that stimulate epistemic curiosity and critical analysis. The instructional trajectories adhere to a systematic continuum moving from engagement to evaluation, mirroring the operational metrics of the 5E framework. The pedagogical sequences balance initial direct instruction with subsequent collaborative peer discourse, predictive hypothesis generation, active model manipulation, and automated data interpretation. Consequently, these digital simulations do not replace the educator but rather complement traditional practices, acting as specialized inquiry environments where students actively construct conceptual meaning, evaluate spontaneous hypotheses, and formulate evidence-based conclusions.

The primary contribution of this research lies in the formulation of an integrated conceptual framework that bridges generative AI co-design with open pedagogy and structured inquiry-based learning models. While conventional educational technology frameworks often assume high baseline resource environments, this study provides a specific operational blueprint for under-resourced schools. By treating generative AI as a democratic co-designer, this paper demonstrates how complex technical programming thresholds can be lowered, enabling non-programmer educators to construct customized, syllabus-aligned digital assets. Furthermore, it expands the theoretical boundaries of open educational practices by transforming static open resources into participatory, curriculum-responsive learning environments.

Despite its conceptual value, certain limitations must be acknowledged. As a conceptual and design-modeling paper, this study lacks immediate empirical verification and field-testing data derived from physical classroom implementations across diverse student demographics. Additionally, while the single-file HTML architecture successfully addresses internet network instability, the framework remains fundamentally dependent on baseline physical infrastructure, such as basic device availability and reliable electrical power supply. To address these limitations, future research should focus on the empirical validation of these AI-generated simulations through longitudinal mixed-methods studies in rural schools to measure actual student learning gains and cognitive load optimization. Future investigations should also explore scalable professional development models that train STEM educators in advanced prompt engineering protocols, alongside expanding the current design principles to accommodate broader interdisciplinary curriculum units

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