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LEARNING SCIENCE BY LIVING THE SCIENTIFIC PROCESS: A QUALITATIVE CASE STUDY FROM AN AFRICAN STEM SECONDARY SCHOOL

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ABSTRACT

This qualitative case study explores how sustained engagement with the scientific process, grounded in local contexts and authentic practice, shapes science learning in an African STEM secondary school. The study draws on a long-term inquiry in which learners and teachers collaboratively produced ethanol from cassava through fermentation and repeated fractional distillation using locally available materials and community-informed methods. Data were generated through teacher reflective journals, learner laboratory records, observations, informal interviews, and comparative analysis of school-based and community-based processes. Thematic analysis focused on learners' reasoning, decision-making, responses to failure, and evolving perceptions of science learning over time. Findings indicate that learners experienced science as an iterative and evolving practice rather than a body of fixed knowledge. Early experimental failure and inconsistent outcomes functioned as productive catalysts for inquiry, prompting data-driven analysis, iterative redesign, and collaborative problem-solving. As the project progressed, learners shifted from answer-seeking to diagnostic and predictive reasoning, demonstrating increased scientific agency and epistemic confidence. Learning beyond conventional laboratory spaces further deepened understanding by exposing learners to real-world constraints, environmental variability, and ethical considerations. The study concludes that authentic, long-term inquiry is essential for developing the scientific competences envisioned in competence-based curricula. It argues that science education in African contexts must move beyond short, outcome-driven practical activities toward learning experiences that allow learners to live the scientific process through sustained engagement with real problems and local knowledge.

KEYWORDS: scientific process; qualitative case study; competence-based education; STEM education in Africa; inquiry-based learning.

1. INTRODUCTION

1.1 Background of the research

Across many education systems worldwide, science education has long been dominated by an instructional culture that prioritises the transmission of established facts, formulas, and procedures. Within such approaches, learners are typically assessed on their ability to recall correct answers or reproduce algorithmic steps, rather than on their capacity to reason scientifically, interrogate evidence, or apply knowledge to unfamiliar situations (Taber, 2018; Osborne, 2014). While this model may support short-term examination success, it often fails to cultivate the habits of mind that define science as a way of knowing—curiosity, scepticism, experimentation, and revision of ideas in light of evidence.

In response to these limitations, contemporary science education reforms increasingly emphasise **competence-based** and **inquiry-oriented** approaches to learning. These reforms advocate for learners' active engagement in scientific practices such as asking questions, designing investigations, analysing data, and constructing explanations grounded in evidence (OECD, 2019; NRC, 2012). Rather than viewing knowledge as static content to be memorised, science is positioned as a dynamic process through which understanding is constructed over time. Within this paradigm, learning is expected to be iterative, collaborative, and closely connected to real-world contexts.

In many African countries, including Zambia, competence-based curriculum frameworks have been introduced with the explicit intention of shifting classroom practice away from teacher-centred transmission toward learner-centred, skills-oriented learning (Ministry of Education, 2023). These frameworks emphasise competences such as critical thinking, problem-solving, creativity, collaboration, and ethical responsibility, positioning science education as a tool for social relevance and sustainable development. However, despite progressive policy intentions, a persistent gap remains between curriculum design and classroom enactment. Studies across African contexts indicate that science teaching often remains examination-driven, textbook-bound, and procedurally focused, with limited opportunities for learners to engage in authentic scientific inquiry (Banda, 2007; Kabombwe & Mulenga, 2019).

This disconnect has significant implications for learner outcomes. When science is presented primarily as finished knowledge rather than as an evolving process, learners may succeed in reproducing answers without developing a meaningful understanding of how scientific knowledge is generated, tested, and refined. Consequently, learners may struggle to transfer scientific concepts beyond the classroom or to apply them creatively to local challenges—an outcome that undermines the broader developmental goals of STEM education in African societies (Ogunniyi, 2011; Aikenhead, 2006).

A growing body of research suggests that **authentic, context-based STEM learning**—particularly when grounded in learners' lived experiences and local knowledge systems—can play a critical role in addressing these challenges. Contextualised learning has been shown to enhance learner engagement, conceptual understanding, and relevance, especially when learners are encouraged to draw connections between school science and community practices (Jegede & Aikenhead, 1999; Odora Hoppers, 2002). Importantly, such approaches challenge deficit views of indigenous and local knowledge by recognising them as legitimate starting points for scientific inquiry rather than obstacles to "modern" science learning.

Within this discourse, however, relatively little empirical work has examined what happens when learners are immersed in the **full scientific process over an extended period of time**, rather than through short, scripted practical activities. Many school-based practicals remain tightly controlled, time-limited, and outcome-driven, offering learners minimal exposure to uncertainty, failure, and iterative redesign—features that are central to authentic scientific practice (Hodson, 2014). As a result, learners may complete science courses having performed experiments without ever truly *doing science*.

This study addresses this gap by presenting a qualitative case study drawn from a long-term STEM learning experience in an African STEM secondary school. The study documents a sustained, school-based project in which learners and teachers collaboratively engaged in the production of ethanol from cassava tubers through fermentation and repeated fractional distillation, using locally available materials and methods closely resembling those employed in many African communities to brew traditional spirits. Rather than functioning as a demonstration or isolated practical exercise, the project unfolded over several months and was characterised by repeated cycles of experimentation, failure, data analysis, redesign, and refinement.

By examining this learning experience, the study seeks to illuminate how scientific understanding and competences emerge when learners are given time to live the scientific process—grappling with uncertainty, negotiating meaning, and constructing knowledge through sustained engagement with real contexts. In doing so, the study contributes to ongoing debates about the nature of effective STEM education in African contexts and offers empirical insights into how competence-based science education can move beyond policy rhetoric into lived classroom practice.

1.2 Research Purpose and Questions

The purpose of this study was to examine how sustained, authentic engagement with the scientific process influences learners' scientific understanding, competences, and dispositions toward STEM learning.

The study was guided by the following research questions:

1. How do learners experience the scientific process when learning is grounded in real-world, locally contextualised STEM projects?
2. What role does failure and iteration play in the development of scientific understanding and competences?
3. How does extending learning beyond conventional classroom and laboratory spaces influence learner engagement and meaning-making?
4. What implications does this experience have for competence-based STEM education in African schools?

2. MATERIALS AND METHODS

2.1 Research Paradigm and Approach

This study was situated within an **interpretivist qualitative research paradigm**, which assumes that knowledge and meaning are socially constructed through interaction, experience, and context (Creswell & Poth, 2018). An interpretivist stance was appropriate given the study's focus on understanding how learners and teachers *experienced* the scientific process over time, rather than measuring predetermined outcomes or testing causal relationships.

Science learning, particularly within competence-based and inquiry-oriented frameworks, involves complex cognitive, social, and affective processes that are best explored through qualitative methods capable of capturing depth, nuance, and change (Denzin & Lincoln, 2018). Accordingly, this study prioritised rich description and participant meaning-making over generalisation.

2.2 Research Design: Qualitative Case Study

A **qualitative case study design** was employed to enable in-depth examination of a bounded learning experience situated within its real-life educational context (Yin, 2018; Stake, 1995). The "case" in this study comprised a long-term STEM learning project involving ethanol production through cassava fermentation and repeated fractional distillation at an African STEM secondary school.

Case study methodology was particularly suitable for this research for three reasons. First, it allowed the study to capture the **processual nature of learning**, including iteration, failure, and redesign—elements often invisible in cross-sectional studies. Second, it supported the exploration of learning as it unfolded across **multiple settings**, including classroom spaces, improvised laboratory environments, and community sites. Third, it enabled the integration of multiple data sources, enhancing analytic depth and credibility through triangulation (Merriam & Tisdell, 2016).

2.3 Context of the Study

The study was conducted at an African STEM secondary school established to promote inquiry-based, interdisciplinary learning aligned with competence-based curriculum reforms. The school serves learners at the senior secondary level and emphasises project-based STEM learning as a core pedagogical approach.

The focal learning activity involved producing ethanol from cassava tubers using fermentation and fractional distillation. Cassava was selected deliberately due to its cultural, economic, and scientific relevance within the local community. The methods and materials employed closely resembled those used by community brewers of traditional spirits, allowing learners to engage with scientific principles embedded in familiar social practices.

Importantly, the project was designed as a **sustained inquiry** spanning several months rather than a short, outcome-driven practical exercise. This extended duration enabled learners to experience science as an iterative process characterised by uncertainty, error, and gradual refinement.

2.4 Participants and Researcher Role

Participants included senior secondary learners enrolled in science subjects and STEM teachers who facilitated the project. Learners worked collaboratively in small groups and participated as part of their regular instructional programme.

The researcher served as both **teacher and researcher**, adopting a **participant-observer role** throughout the study. Teacher-researcher approaches are well established in educational research, particularly in studies aimed at understanding classroom practice from an insider perspective (Cochran-Smith & Lytle, 2009). This positionality allowed for sustained observation, reflexive engagement, and deep contextual understanding.

Recognising the dual role's potential influence on interpretation, reflexivity was maintained through regular reflective journaling and deliberate attention to distinguishing instructional decisions from analytic claims (Finlay, 2002).

2.5 Data Generation Methods

Multiple qualitative data sources were used to capture different dimensions of the learning experience and enhance credibility through triangulation (Patton, 2015).

2.5.1 Teacher Reflective Journals

The researcher maintained reflective journals throughout the project, documenting instructional decisions, learner responses, emerging challenges, and shifts in understanding. Reflective journaling enabled ongoing sense-making and provided insight into pedagogical dynamics and evolving learner engagement (Schön, 1983).

2.5.2 Learner Artefacts and Laboratory Records

Learner-generated artefacts included laboratory notebooks, experimental data tables, sketches of apparatus designs, and written reflections. These artefacts provided direct evidence of learners' reasoning processes, decision-making, and iterative redesign over time.

2.5.3 Observations

Non-participant and participant observations were conducted during laboratory sessions, improvised experimental setups, and community visits. Observation notes focused on learner interactions, questioning patterns, use of evidence, and responses to unexpected outcomes. Observational data allowed the study to capture social and dialogic dimensions of learning often absent from written records (Angrosino, 2017).

2.5.4 Informal Interviews and Conversations

Informal, conversational interviews were conducted with learners and teachers during and after project activities. These interactions provided opportunities for participants to articulate their thinking, reflect on challenges, and express evolving perceptions of science learning. Informal interviews were particularly appropriate given the extended duration of the project and the need to minimise disruption to learning activities (Kvale & Brinkmann, 2015).

2.5.5 Community-Based Observations and Comparative Samples

Learners and teachers visited local community brewers to observe fermentation and distillation practices and to engage in dialogue regarding techniques developed through experiential knowledge. Samples collected from these settings were analysed alongside school-produced samples, generating comparative data that enriched interpretation of process efficiency, environmental factors, and contextual constraints.

2.6 Data Analysis

Data analysis followed a **thematic analysis approach**, conducted iteratively alongside data generation (Braun & Clarke, 2006). The process involved:

1. Familiarisation with data through repeated reading of journals, artefacts, and observation notes
2. Initial open coding to identify patterns related to inquiry, failure, iteration, collaboration, and context
3. Grouping codes into categories reflecting shared meanings
4. Developing broader themes that captured recurring interpretive patterns across data sources

Analysis prioritised **process over outcome**, focusing on how learners' scientific reasoning evolved over time rather than on final experimental results alone.

2.7 Trustworthiness and Rigour

To enhance the study's trustworthiness, strategies aligned with qualitative research standards were employed (Lincoln & Guba, 1985):

- **Credibility** was supported through prolonged engagement, triangulation of data sources, and persistent observation.
- **Dependability** was addressed by maintaining detailed records of data generation and analytic decisions.
- **Confirmability** was strengthened through reflexive journaling and the inclusion of verbatim learner excerpts and observational evidence.
- **Transferability** was supported through thick description of context and process, allowing readers to assess relevance to their own settings.

2.8 Ethical Considerations

Ethical principles guiding educational research were observed throughout the study. Learner participation occurred as part of regular instructional activity. Additionally, safety considerations were prioritised during experimental work, particularly when operating outside conventional laboratory environments.

2.9 Methodological Limitations

As a single-case qualitative study, findings are not intended to be statistically generalisable. However, the study offers **analytical generalisation**, contributing insights into how competence-based STEM learning can be enacted in similar contexts (Yin, 2018). The teacher-researcher role may introduce interpretive bias; however, reflexivity and triangulation were employed to mitigate this risk.

3. RESULTS AND DISCUSSION

The findings are organised thematically to illustrate how learners' scientific understanding and competences evolved over time through sustained engagement with an authentic, locally contextualised scientific process. Rather than presenting outcomes as isolated results, this section foregrounds process, decision-making, and meaning-making as central features of learning, integrating empirical evidence with interpretation.

3.1 Instructional Decisions and the Structuring of Inquiry

A defining feature of the learning experience was the set of deliberate instructional decisions that positioned learners as active constructors of knowledge rather than recipients of predefined procedures. As summarised in Table 1, instructional choices prioritised openness, uncertainty, and iteration over efficiency or rapid syllabus coverage.

Table 1: Key Instructional Decisions and Pedagogical Intent.

Instructional Decision	Pedagogical Rationale	Observed Impact
Use of local cassava and community brewing methods	Legitimate learners' prior knowledge and local practices	Increased learner engagement and ownership
Absence of prescribed experimental steps	Encourage inquiry and decision-making	Learners debated methods and justified choices
Acceptance of early low-purity results	Reframe failure as data	Sustained motivation and deeper questioning
Extended project duration (months)	Allow iterative learning cycles	Progressive refinement of reasoning
Relocation to improvised learning spaces	Increase authenticity	Enhanced problem-solving and safety awareness
Comparative analysis with community samples	Situate science socially	Development of evaluative and ethical reasoning

These decisions legitimised learners' prior knowledge, encouraged inquiry-driven decision-making, and reframed early experimental failure as a productive source of data rather than as error.

Empirically, these conditions created sustained learner engagement, deeper questioning, and progressive refinement of reasoning. Learners experienced science not as a task to be completed but as an evolving process requiring judgement and persistence. This finding directly addresses the first research question, demonstrating that when learning is grounded in real-world, locally meaningful STEM projects, learners experience the scientific process as iterative, uncertain, and participatory rather than linear and confirmatory. This supports critiques of outcome-driven practical work (Hodson, 2014) and aligns with contemporary views of science as an evolving practice (Osborne, 2014; NRC, 2012).

As shown in Figure I, beginning the project with the harvesting and preparation of cassava tubers positioned local practice as the entry point into scientific inquiry, reinforcing relevance and learner ownership.

Figure I. **Learners collecting and preparing cassava tubers as locally sourced raw material for the ethanol fermentation project.**

3.2 Learner Engagement, Interaction, and Questioning Patterns

Observation data and learner artefacts indicate that learners engaged in collaborative dialogue characterised by exploratory rather than answer-seeking questioning. As illustrated in Table 2, questioning patterns evolved from descriptive and observational questions to causal, diagnostic, and ultimately predictive forms as learners gained confidence in interpreting evidence.

Table 2

Evolution of Learner Questioning Patterns.

Phase of Project	Dominant Question Types	Examples
Initial phase	Descriptive / observational	"What is happening during fermentation?"
Early experimentation	Causal	"Why is alcohol separating when heated?"
Iterative phase	Diagnostic	"Where did we lose ethanol?"
Advanced phase	Predictive / evaluative	"If we change the condenser length, will purity increase?"

This progression reflects a shift in how learners experienced the scientific process: from observing phenomena to actively interrogating causes and anticipating outcomes. Learners increasingly questioned one another's assumptions and responded to questions with further inquiry rather than deferring to the teacher, indicating a redistribution of epistemic authority. These interaction patterns reinforce sociocultural perspectives on learning, which emphasise dialogue and shared meaning-making as central to knowledge construction (Vygotsky, 1978). Figure II visually captures this social dimension of inquiry, showing learners collectively observing, discussing, and interpreting experimental processes.

Figure II. Learners collaboratively observing, discussing, and monitoring the distillation process within an improvised experimental space, illustrating peer interaction, shared decision-making, and collective reasoning during inquiry.

Together, these findings demonstrate that authentic inquiry environments foster learner agency and scientific reasoning through social interaction rather than individual performance.

3.3 Failure and Response to Unexpected Outcomes

Early ethanol purity levels of 52–58% represented a critical moment in the learning trajectory. As shown in Table 3, learners' immediate reactions included surprise and frustration; however, these responses quickly transitioned into analytical actions such as error analysis, review of fermentation conditions, and comparison with previous data.

Table 3

Learner Responses to Unexpected Outcomes.

Outcome	Immediate Reaction	Subsequent Action
Low ethanol purity	Surprise, debate	Error analysis discussions
Inconsistent results	Frustration	Review of fermentation conditions
Decline in purity after modification	Confusion	Comparison with previous data
Safety challenges in open space	Caution	Redesign of heat control methods

Rather than disengagement, failure functioned as an epistemic resource that deepened inquiry. Learners' reflections—such as *"When it didn't work, we didn't feel stupid. We felt like something was hiding and we needed to find it"*—illustrate a shift from performance-oriented thinking to evidence-oriented reasoning. This finding directly answers the second research question by demonstrating that failure and iteration were central to the development of scientific understanding and competences. The results resonate with research on productive failure, which highlights the role of error in strengthening conceptual understanding when framed appropriately (Kapur, 2008).

3.4 Learners' Reasoning Processes and Evidence-Based Decision-Making

As the project progressed, learners increasingly grounded decisions in empirical evidence rather than intuition or authority. Table 4 documents learners' use of recorded data, causal reasoning, systems thinking, and error attribution across laboratory records, group discussions, and design sketches.

Table 4

Evidence of Learners' Scientific Reasoning.

Reasoning Dimension	Indicators	Evidence Source
Use of data	Referring to recorded temperatures and volumes	Lab notebooks
Causal reasoning	Linking purity to temperature control	Group discussions
Systems thinking	Recognising interactions between components	Design sketches
Error attribution	Identifying leaks or incomplete fermentation	Observation notes

This shift marked a transformation in learner reasoning, captured in the learner's statement: *"Before, we guessed. Now we argue using our results."* Authority within the learning environment became grounded in evidence rather than teacher position, aligning with inquiry-based learning principles (Osborne, 2014). Learner agency thus emerged not as a predefined instructional outcome but as a consequence of authentic participation in scientific decision-making.

3.5 Iterative Redesign and Learning Over Time

Repeated redesign was a central mechanism through which understanding deepened. As shown in Table 5, each iteration was incremental and evidence-driven, addressing specific weaknesses identified through prior testing. Over time, learners demonstrated increasing ability to anticipate the consequences of design changes before implementation, indicating the development of predictive reasoning.

Table 5: Examples of Iterative Redesign Across Project Phases.

Iteration	Design Modification	Rationale	Outcome
1	Extended fermentation time	Suspected incomplete fermentation	Slight purity increase
2	Improved sealing of joints	Prevent vapour loss	Reduced ethanol loss
3	Modified condenser length	Improve condensation efficiency	Noticeable purity gain
4	Improved heat regulation	Stabilise boiling point	Achieved high consistency

Figure III illustrates how learners designed and refined their own fermentation and distillation apparatus, grounding abstract scientific principles in material construction and iterative testing. These findings reinforce the importance of time as a pedagogical resource and directly support competence-based education goals that prioritise process skills over rapid content coverage.

Figure III Left. Learners presenting a self-constructed fermentation and simple distillation apparatus similar to the design used by community spirit brewers.

Figure III Right. Refined fractional distillation apparatus inserted with glass marbles used during later stages of the project, illustrating improved separation efficiency achieved through iterative redesign and enhanced control of heat transfer and condensation.

3.6 Learning Beyond the Classroom: Environmental and Contextual Constraints

Relocating experimentation to an improvised piggery space introduced environmental and logistical constraints absent from conventional laboratories. As summarised in Table 6, learners had to manage heat instability, safety concerns, space limitations, and variable ambient conditions.

Table 6: Environmental Factors and Learner Adaptations.

Environmental Factor	Challenge	Learner Response
Open airflow	Heat instability	Shielding heat sources
Limited ventilation	Safety concerns	Modified setup orientation
Variable ambient temperature	Inconsistent results	Adjusted heating duration
Space constraints	Equipment layout issues	Redesigned apparatus arrangement

These challenges prompted learners to engage in systems thinking, risk assessment, and ethical judgement, extending learning beyond procedural competence. Observation data indicate that learners frequently paused experiments to discuss safety and environmental factors, reflecting heightened situational awareness. Figure IV illustrates how open-fire heating in an improvised space required continuous judgement and adaptation, directly addressing the third research question. Consistent with situated learning theory, these findings demonstrate that learning in authentic environments strengthens learners' ability to apply scientific reasoning under real-world constraints (Lave & Wenger, 1991).

Figure IV. Ethanol distillation conducted in an improvised experimental space using open-fire heating, requiring learners to manage temperature control, safety, and environmental constraints in real-world conditions.

3.7 Comparative Analysis of School and Community-Based Processes

Comparative testing of school-produced and community-produced ethanol further enriched learners' evaluative reasoning. As shown in Table 7, learners identified trade-offs between precision, efficiency, safety, and contextual adaptation across the two settings.

Table 7

Comparative Data and Interpretive Insights.

Aspect	School-Based Process	Community-Based Process	Learner Interpretation
Equipment	Modified improvised apparatus	Traditional setups	Efficiency linked to experience

Environmental control	Variable	Context-adapted	Trade-offs between control and practicality
Purity levels	Gradually optimised	Variable but stable	Process consistency matters
Safety awareness	Explicit discussion	Implicit practice	Ethics and responsibility differ

Learners' reflections—such as *"They don't measure everything, but they know exactly when to stop"*—indicate an emerging appreciation of science as a contextual practice shaped by experience, purpose, and environment. These findings challenge deficit narratives surrounding indigenous knowledge and support culturally responsive STEM education that bridges school science and community practice without romanticising either (Aikenhead, 2006; Jegede & Aikenhead, 1999; Ogunniyi, 2011).

3.8 Shifts in Learners' Perceptions of Science Learning

Over time, learners' perceptions of science learning shifted markedly. As shown in Table 8, learners moved from viewing science as the pursuit of correct answers toward understanding it as a process of questioning, evidence-based reasoning, and patience.

Table 8

Evolving Learner Perceptions of Science

Early Perception	Later Perception
Science is about correct answers	Science is about good questions
Experiments must work	Experiments teach even when they fail
Teacher knows the solution	Evidence decides
Mistakes are bad	Mistakes are useful

Learner statements such as *"Science is not about being right fast—it's about being patient"* reflect the development of epistemic patience, a disposition central to authentic scientific practice but rarely cultivated in syllabus-driven classrooms.

3.9 Integrated Synthesis and Implications

Collectively, the findings demonstrate that learners developed scientific competences through sustained engagement with uncertainty, failure, and iteration; that instructional openness enabled deeper reasoning and collaboration; and that authentic, context-rich environments strengthened ethical, practical, and evaluative thinking. Science learning shifted from content acquisition to epistemic participation, directly addressing all four research questions.

Figure V illustrates the culmination of this process, showing learners presenting ethanol and ethanol-based products to a wider audience. This public articulation of learning demonstrates transfer, communication, and application of scientific understanding beyond the experimental space.

Figure V. Learner presenting ethanol and ethanol-based products (methylated spirit and hand sanitisers) developed through the cassava fermentation and distillation project during a public STEM exhibition, demonstrating transfer of scientific inquiry into tangible outcomes.

4. CONCLUSION

This qualitative case study examined how sustained engagement with the scientific process, grounded in local contexts and authentic practice, shapes science learning in an African STEM secondary school. Drawing on a long-term inquiry into ethanol production from cassava, the study demonstrates that meaningful scientific understanding emerges when learners actively live the scientific process rather than merely reproduce its outcomes.

The findings show that learners experienced science as an evolving practice characterised by questioning, experimentation, evidence interpretation, and iterative refinement. Over time, learners shifted from seeking correct answers to engaging in diagnostic and predictive reasoning, reflecting a fundamental transformation in how they understood science and their role within it. Failure and iteration functioned as central learning mechanisms, prompting deeper analysis, redesign, and evidence-based decision-making rather than disengagement.

Extending learning beyond conventional classroom and laboratory spaces further enriched understanding by exposing learners to real-world constraints, ethical considerations, and contextual variability. These experiences reinforced the situated nature of scientific knowledge and strengthened competences such as persistence, systems thinking, and adaptive reasoning.

Collectively, the findings underscore important implications for competence-based STEM education in African contexts. Long-term, authentic inquiry must be deliberately supported within curricula, assessment practices, and teacher preparation if learners are to develop the competences envisioned in policy frameworks. Recognising local knowledge and community practices as legitimate resources for STEM learning is essential for relevance and depth.

Ultimately, this study affirms that scientific understanding cannot be rushed, scripted, or memorised—it must be lived. When learners are given time, responsibility, and real problems to engage with, science education moves beyond content coverage toward the development of capable, reflective, and contextually grounded scientific thinkers.

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