Teacher Educators’ Conceptualisations of Integrated STEM Education and Pedagogical Practice in Zambian Higher Education: A Multi-Case Qualitative Study

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Abstract: Science, Technology, Engineering, and Mathematics (STEM) education has become a major policy priority globally because of its recognised contribution to innovation, technological adaptation, workforce development, and long-term economic competitiveness. Although existing scholarship has concentrated on school-level teachers, limited empirical attention has been given to teacher educators who prepare future teachers and whose pedagogical orientations strongly influence educational reform. This study examined how teacher educators in selected public higher education institutions in Zambia conceptualise integrated STEM education, how they report applying STEM-related pedagogies, and which institutional conditions shape implementation readiness. A qualitative multi-case study design was employed across four purposively selected teacher education institutions involving thirty STEM-related teacher educators. Data were generated through open-ended questionnaires, semi-structured interviews, and focus group discussions, and analysed using thematic analysis. The findings show that while participants widely recognised the strategic importance of STEM education, conceptual understanding remained uneven and frequently fragmented. STEM was commonly interpreted through selected pedagogical attributes such as student-centred learning, critical thinking, practical engagement, self-directed learning, and interdisciplinary teaching, yet few participants demonstrated a coherent understanding of STEM as a fully integrated instructional framework. Pedagogically, lecturers reported occasional use of exploratory problem solving, project-based tasks, real-life applications, and hands-on activities, but no sustained evidence of interdisciplinary artefact production or structured STEM design was identified across study sites. Major constraints included limited formal pedagogical knowledge of STEM, weak institutional collaboration, and persistent disciplinary teaching structures, while lecturer willingness to learn emerged as an important enabling condition. The study concludes that teacher educator readiness represents the critical missing institutional layer in Zambia’s STEM reform architecture and recommends development of a harmonised teacher education framework aligned with competence-based education policy to guide interdisciplinary STEM implementation.

Keywords: *STEM Education, Teacher Educators, STEM, Pedagogical Practice, Higher Education, Zambia.*

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I. INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) education has become a strategic priority within global education reform because of its demonstrated relationship with innovation capacity, technological advancement, labour productivity, and long-term economic competitiveness. Countries that have successfully strengthened STEM systems have generally linked educational investment to wider national development objectives, particularly scientific capability, industrial growth, and workforce preparedness for technologically complex economies. In contemporary educational discourse, STEM is no longer understood simply as the parallel teaching of four disciplinary subjects, but increasingly as an integrated pedagogical framework through which learners engage in interdisciplinary problem solving, inquiry, design thinking, and application of knowledge to authentic societal challenges (Thibaut, Ceuppens, De Loof, De Meester, Goovaerts, Struyf, ... & Depaepe, 2018; Bybee, 2010).

This conceptual shift from disciplinary instruction toward integrated STEM emerges from the recognition that contemporary social and economic challenges rarely occur within isolated disciplinary boundaries. Consequently, effective STEM education requires deliberate pedagogical designs that connect disciplinary knowledge through real-world contexts, collaborative inquiry, and solution-oriented learning experiences. Systematic reviews of integrated STEM instruction consistently identify disciplinary integration, problem-centred learning, inquiry processes, design activity, and cooperative learning as core characteristics of effective STEM implementation (Thibaut et al., 2018; Portillo-Blanco, Deprez, De Cock, Guisasola & Zuza, 2024).

Across Sub-Saharan Africa, STEM education has increasingly been positioned as a strategic mechanism for accelerating economic transformation, improving technological self-reliance, and expanding participation in science-related careers. However, implementation across many countries remains uneven because policy ambition frequently exceeds institutional preparedness (Sakala & Banda, 2025; Chirinda, Sunzuma, & Muredzi, 2025) Persistent constraints include limited teacher capacity, inadequate infrastructure, weak interdisciplinary curriculum frameworks, and insufficient professional development systems. In several contexts, reforms have prioritised curriculum introduction without corresponding investment in teacher preparation structures, producing implementation gaps between policy intention and classroom practice.

Zambia presents a particularly important case within this wider discussion. In response to national development priorities and concerns about scientific literacy, the Ministry of Education introduced STEM curricula in selected secondary schools, initially piloted in fifteen of fifty-four designated STEM schools (Magasu, Mutale, & Gondwe, 2022). The reform aimed to increase learner participation in science pathways, strengthen technological competence, and align educational outputs with labour market demands (National Science Centre, 2018; 2020). However, after approximately two years of implementation, the initiative was withdrawn. Available evidence attributes this reversal largely to implementation weaknesses, particularly inadequate teacher preparedness, weak institutional coordination, and limited instructional clarity regarding interdisciplinary STEM integration (Magasu et al., 2022).

Some studies in Zambia including Maambo (2023) indicate that many teachers interpreted STEM primarily as practical science teaching rather than structured interdisciplinary integration. As a result, classroom practices often remained discipline-bound even where policy documents advocated integration. More importantly, emerging evidence suggested that graduate teachers entering schools had received limited exposure to STEM methodologies during training (Shernoff, Sinha, Bressler, & Ginsburg, 2017; Berry, Carpendale, & Mulhall, 2025). This raises concern that implementation difficulties may originate within teacher education institutions rather than schools alone. This places teacher educators at the centre of STEM reform. Universities and colleges responsible for teacher preparation occupy a strategic position because they shape pedagogical identities, instructional habits, and curriculum interpretation before teachers enter school systems.

When STEM education is reintroduced nationally without strengthening teacher education first, newly trained graduates may continue reproducing traditional subject-isolated pedagogies, thereby undermining competence-based education reforms currently underway. This study therefore addresses an important empirical and policy gap by examining how teacher educators in selected higher education institutions in Zambia conceptualise integrated STEM education, how they report applying STEM-related pedagogies, and which institutional conditions facilitate or constrain implementation.

II. LITERATURE REVIEW

➢ *Conceptual Foundations of STEM Education*

The rapid global expansion of Science, Technology, Engineering, and Mathematics education has generated extensive scholarly attention because of its perceived capacity to strengthen innovation systems, improve productivity, and prepare learners for technologically complex economies. Although STEM education is now widely embedded in policy discourse, its conceptual interpretation remains contested across educational contexts. The most widely accepted position in contemporary scholarship defines STEM education as the intentional integration of disciplinary knowledge in ways that enable learners to investigate authentic problems through inquiry, design, experimentation, and collaborative reasoning rather than through isolated subject instruction (Lowrie, Logan, & Larkin, 2017; Haamasama,2025; Hoa, 2025). Bybee (2010) argues that STEM becomes educationally meaningful only when the four disciplines function as mutually reinforcing knowledge domains within a coherent pedagogical process rather than as adjacent curriculum labels. This distinction remains analytically important because many institutions adopt STEM terminology without corresponding instructional transformation.

Recent scholarship demonstrates that integrated STEM education differs fundamentally from traditional science enrichment or mathematics enhancement programmes because integration requires pedagogical restructuring rather than curriculum addition. Thibaut et al.'s (2018) systematic review identifies interdisciplinary content integration, problem-centred instruction, inquiry processes, design-based learning, and cooperative engagement as the principal features distinguishing authentic STEM teaching from conventional classroom practice. Similarly, recent synthesis work by Portillo-Blanco et al., (2024) shows that across diverse educational systems, successful STEM implementation depends less on policy declaration and more on whether educators possess operational understanding of how disciplinary integration functions in instructional design. Where such operational understanding is weak, STEM frequently collapses into practical activity that remains structurally discipline-bound.

- *Benefits of STEM Education*

Several literature such as Biasutti &El-Deghaidy (2014), El-Deghaidy & Mansour 2015), Wahid & Talib (2017), Ismail (2018), NCS (2018) and Talib, Alias, Matore, & Abdullah (2025) and has expounded on the benefits of STEM education. Some benefits include enhancing higher-order thinking skills and developing 21st-century skills, which can contribute to solving 21st-century challenges and lead to job creation and value addition. Teachers are key to successful STEM integration in the Classroom (Wahid & Talib, 2017). Nonetheless, several things must be considered: whether teachers integrate STEM in schools successfully and whether learners ultimately benefit from STEM education. For instance, El-Deghaid and Mansour (2015, p. 52) suggest that for teachers to introduce STEM education in their schools they need first of all to have '…deep content knowledge, strong belief in innovative teaching strategies that has at its core student centred teaching, interdisciplinary learning to building bridges across subjects, and the development of strong teams that can create a culture of success in schools through professional communities'.

Other researchers, such as Wahid and Talib (2017) and Bell (2016), also indicate that teachers should have the necessary facilities, models, and guidelines to follow. This can be possible with the input of well-informed university-level teacher educators, trainers, or lecturers among other key stakeholders. The role of teacher educators and trainers in preparing trainee teachers, whether in-service or pre-service, to enact STEM Education cannot be overemphasised. There generally is limited empirical attention given to teacher educators who prepare future teachers and whose pedagogical orientations strongly influence educational reform compared to school-level teachers. This study examined how teacher educators in selected public higher education institutions in Zambia conceptualise integrated STEM education, how they report applying STEM-related pedagogies, and which institutional conditions shape implementation readiness.

- *STEM Pedagogy and Teacher Education*

Within teacher education, the challenge becomes more complex because teacher educators must not only understand STEM conceptually but also model it pedagogically for future teachers. Darling-Hammond, 2017 as well as Darling-Hammond, Hyler, Wojcikiewicz and Rushing (2025) demonstrate that teacher preparation systems exert long-term influence on school reform because pre-service teachers often reproduce the instructional models they experience during training. Consequently, where university lecturers themselves remain uncertain about integrated STEM pedagogy, school-level reform becomes structurally constrained.

A growing body of STEM teacher education literature shows that teacher educators often endorse STEM philosophically while struggling to translate it into interdisciplinary teaching practice. Margot and Kettler (2019), Li, Wang, Xiao, and Froyd (2020) and Li, Wang, Xiao and Wilson (2022). in their systematic reviews found that educators frequently interpret STEM through practical learning, student-centred instruction, or problem solving while omitting engineering design, technological mediation, and explicit disciplinary coordination. This pattern is particularly relevant to the present study because participants similarly associated STEM with student leadership, self-directed learning, and critical thinking while often remaining uncertain about how science, mathematics, technology, and engineering should be deliberately connected in actual instruction.

- *STEM Reform and Teacher Education in Zambia*

Within Zambia, available literature remains limited but highly consistent in identifying teacher preparedness as a central implementation challenge. Existing studies indicate that the initial STEM curriculum introduced in selected secondary schools encountered serious pedagogical difficulties because many teachers lacked practical understanding of interdisciplinary STEM methodologies. Evidence published in (Magasu et al., 2022: Haamasama, 2025) shows that the withdrawal of the STEM curriculum reflected not only policy-level difficulties but also deep instructional readiness problems.

However, earlier Zambian studies focused primarily on secondary school teachers and did not sufficiently examine teacher educators responsible for preparing graduate teachers before entry into schools. This leaves an important empirical gap because weaknesses observed in school implementation may originate within university teacher education systems themselves.

- *Analytical Position of the Present Study*

The literature converges around one central conclusion: sustainable STEM implementation depends on the interaction of conceptual clarity, pedagogical modelling, institutional collaboration, and structural support. Weakness in any one of these dimensions reduces the likelihood that STEM becomes durable educational practice. The present study builds on this analytical position by examining teacher educators not merely as curriculum transmitters, but as institutional gatekeepers of STEM reform whose conceptualisations shape pedagogical practice, graduate teacher competence, and ultimately national implementation trajectories.

III. METHODOLOGY

This study employed a qualitative multi-case study design to examine teacher educators' conceptualisations of integrated Science, Technology, Engineering, and Mathematics education and the pedagogical practices through which STEM-related teaching is enacted within selected higher education institutions in Zambia. A qualitative design was appropriate because the study sought to generate in-depth understanding of how teacher educators interpret STEM education, how they describe its pedagogical application within teacher preparation programmes, and which

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institutional conditions shape implementation. Qualitative inquiry is particularly suited to educational contexts where meanings, beliefs, experiences, and institutional practices require contextual interpretation rather than reduction to numerical measurement alone (Creswell, 2018).

The multi-case study approach was selected because STEM implementation in teacher education is institutionally embedded and cannot be adequately understood outside the organisational contexts in which lecturers work. According to Yin (2018), case study research is appropriate when a contemporary educational phenomenon must be examined within its real-life institutional environment, especially where contextual conditions are inseparable from the phenomenon itself. In this study, each participating institution constituted a separate analytical case, while cross-case comparison enabled identification of common patterns and institutional differences in STEM understanding and pedagogical enactment.

➢ *Study Sites and Participant Selection*

The study was conducted in four purposively selected higher education institutions offering STEM-related teacher education programmes in Zambia. These institutions were selected because they play a strategic role in preparing secondary school teachers in science, mathematics, and related disciplines, and therefore represent critical sites for examining foundational readiness for future STEM reform. The pseudo names for the four participating public universities: UNIV A, UNIV B, UNIV C and UNIV D. Selection across institutions allowed variation in institutional history, programme structure, and disciplinary culture, thereby strengthening analytical comparison.

Purposive sampling was used to identify participants because the study required respondents directly involved in teaching STEM-related subjects within teacher education programmes. Purposive sampling remains appropriate when participants possess specialised knowledge directly relevant to the research objectives. Thirty (30) teacher educators participated in the study. Inclusion criteria required that participants be actively engaged in teacher preparation within STEM-related subject areas and possess at least three years of teaching experience in higher education. Participants were drawn from science education, mathematics education, agricultural science, and related disciplinary areas linked to teacher preparation.

Participant distribution reflected institutional availability and programme size. Institutional records showed variation across sites, with one university contributing nine (9) participants, another three (3) participants, a third (14) fourteen participants, and the fourth four (4) participants. Although institutional identities were retained for methodological transparency, analytical coding during interpretation focused on cross-case patterns rather than institutional ranking.

➢ *Data Collection Procedures*

Data were collected through three complementary methods: questionnaires with open-ended and some closed-ended questions, semi-structured interviews, and focus group discussions. The use of multiple methods allowed triangulation, thereby strengthening credibility by capturing both individual and collective perspectives on STEM understanding and pedagogical practice.

The questionnaires were first administered to all thirty participants to establish baseline information regarding self-assessed understanding of STEM education, reported pedagogical practices, and perceptions of institutional support. The questionnaires contained both closed and open-ended items, enabling descriptive categorisation while preserving opportunities for qualitative elaboration.

Semi-structured interviews were subsequently conducted with selected participants to deepen understanding of conceptual and pedagogical issues emerging from questionnaire responses. Interviews allowed participants to explain how they understood STEM education, describe how they used STEM-related teaching approaches, and identify institutional barriers affecting implementation. Semi-structured interviewing was preferred because it provides sufficient flexibility for probing while maintaining consistency around predetermined analytical themes (Kothari & Garg, 2004; Anthony, Miller-Day, Dupuy, Ventura, Hodges, Alonso-Pecora, & Dimas, 2025; Geampana, & Perrotta, 2025).

Focus group discussions were then conducted to capture collective institutional perspectives and examine how teacher educators negotiate meanings of STEM education within shared professional contexts. Focus groups were particularly useful because educational practices are socially shaped, and interaction among participants often reveals institutional norms, assumptions, and shared constraints (Geampana, & Perrotta, 2025)

➢ *Data Analysis*

Data were analysed through thematic analysis supported by limited descriptive statistics derived from questionnaire responses. Thematic analysis was selected because it allows systematic identification, organisation, and interpretation of patterned meaning across qualitative datasets while preserving interpretive depth (Sjöström & Dahlgren, 2002; Kushnir, 2025).

Analysis proceeded through stages. First, all questionnaire narratives, interview transcripts, and focus group records were read repeatedly to achieve data familiarisation. This stage allowed preliminary recognition of recurring conceptual and pedagogical patterns. This was followed by, open coding which was undertaken to identify meaningful units directly linked to the study objectives. Initial codes included expressions such as student-centred learning, self-directed learning, critical thinking, practical teaching, project work, real-life problem solving, limited knowledge, weak collaboration, and disciplinary separation. Thirdly, related codes were clustered into broader thematic categories through axial coding. For example, student-centred learning, self-directed learning, critical thinking, and practical engagement were grouped under conceptual

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interpretations of STEM education. Project work, exploratory tasks, real-life applications, and hands-on activities were grouped under pedagogical enactment. Limited knowledge, weak collaboration, and disciplinary separation formed the institutional constraints theme. Fourthly, themes were refined through iterative comparison across cases to identify both shared patterns and institutional variation. Independent review of coded themes was conducted by members of the research team before consensus was reached, thereby strengthening analytical consistency.

Descriptive statistics were then used to summarise selected questionnaire frequencies, particularly self-assessed levels of STEM understanding across institutions. These numerical summaries were used only to support thematic interpretation rather than to shift the study toward quantitative explanation.

➢ *Theoretical Framework*

Interpretation was guided by the integrated STEM framework associated with Roehrig Dare, Ellis and Ring-Whalen (2021), STEM integration research paradigm (Moore, 2010) and related STEM integration scholarship including by Ortiz-Revilla, Greca, and Arriassecq (2022)., which conceptualise STEM learning as intentional connection of disciplinary knowledge through authentic problem solving and design-oriented activity. The study builds upon these because they provide clear analytical criteria for distinguishing fragmented disciplinary teaching from genuine interdisciplinary STEM integration.

Within the frameworks, authentic STEM practice requires more than practical classroom activity. It requires deliberate interaction among disciplinary forms of knowledge, design orientation, and observable application through problem solving or artefact generation. They were also especially important in interpreting the absence of STEM-generated artefacts across participating institutions despite lecturers' reports of occasional practical teaching.

➢ *Trustworthiness*

Trustworthiness can be strengthened through established qualitative procedures addressing credibility, dependability, confirmability, and transferability (Gunawan, 2015; Adler, 2022). Credibility was enhanced through methodological triangulation across questionnaires, interviews, and focus groups. Cross-case comparison across four institutions further reduced the likelihood that findings reflected isolated institutional conditions. Member checking was undertaken during interviews through clarification of responses where participants appeared conceptually inconsistent or ambiguous.

Dependability was strengthened through careful documentation of coding stages, thematic development, and analytical decisions throughout the research process. Confirmability was supported by maintaining an audit trail linking thematic interpretations directly to original participant statements. Transferability was strengthened through detailed description of institutional context, participant characteristics, and methodological procedures, allowing readers to assess relevance to similar teacher education environments.

➢ *Ethical Considerations*

Ethical procedures were observed throughout the study. Institutional approval was obtained prior to fieldwork. All participants gave informed consent before participation and were informed about the study purpose, confidentiality protections, and their right to withdraw without consequence. Identification codes rather than personal names were used during transcription and reporting to preserve anonymity. Data were securely stored and used exclusively for research purposes.

IV. RESULTS

The findings are presented according to the three objectives that guided the study: teacher educators' conceptual understanding of integrated STEM education, pedagogical practices associated with STEM-related teaching within teacher education programmes, and institutional factors that facilitate or constrain implementation. Across all four participating institutions, the analysis revealed a consistent pattern in which teacher educators strongly endorsed the importance of STEM education while demonstrating uneven conceptual clarity and limited pedagogical enactment. Although some participants initially expressed confidence in their understanding of STEM education, deeper probing during interviews and focus group discussions revealed important conceptual inconsistencies and institutional limitations.

➢ *Teacher Educators' Conceptual Understanding of STEM Education*

Questionnaire responses initially suggested moderate confidence in STEM understanding across participants. Table 1 below shows the responses.

Table 1 Responses Showing Confidence in STEM Understanding

	UNI A	**UNI B**	**UNI C**	**UNI D**	**Total**
I don't know/I am not sure	0	0	7	0	7(23%)
Good/fairly well	5	3	4	3	15(50%)
Very good/very well/I know a lot	4	0	3	1	8(27%)
Total	9	3	14	4	30 (100%)

Of the thirty teacher educators, fifteen rated themselves as having fair or good understanding of STEM education, eight reported very good understanding, and seven indicated uncertainty or openly stated that they did not understand the concept adequately.

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However, these self-assessments became less stable during interviews because several participants who initially reported strong understanding later struggled to explain STEM as an integrated pedagogical framework.

- *One Participant Openly Acknowledged Limited Conceptual Familiarity:*

"I do not think I know enough about STEM education because I have not paid serious attention to it."

Another participant explained that although the term was familiar, practical meaning remained unclear:

"We hear about STEM, but how it should actually be organised in teaching is not always very clear."

These statements indicate that exposure to STEM terminology had not necessarily translated into operational pedagogical understanding.

Across interviews and focus group discussions, five dominant conceptual interpretations emerged.

Firstly, many participants described STEM education as student-centred learning, emphasising that learners rather than lecturers should drive classroom activity. Participants repeatedly associated STEM with increased learner responsibility, active engagement, and reduced teacher dominance. Secondly, STEM was frequently described as self-directed learning, where learners independently search for solutions rather than relying entirely on lecturer explanation. Thirdly, participants strongly associated STEM with critical thinking, particularly the capacity to analyse problems and generate reasoned responses. Fourthly, STEM was described as practical engagement, with emphasis placed on hands-on activity and real-life application.

The fifth dominant interpretation is linked to interdisciplinary learning. Some participants identified interdisciplinary teaching as an important characteristic, acknowledging that STEM ideally involves combining multiple subject areas. Although these interpretations reflect recognised dimensions of STEM pedagogy, participants often articulated them as separate attributes rather than interconnected components of a coherent instructional model. Very few respondents were able to explain explicitly how science, mathematics, technology, and engineering should be deliberately connected during teacher education instruction.

➢ *Pedagogical Practices Associated with STEM Integration*

The second objective examined how lecturers reported integrating STEM-related pedagogies within lecture rooms and laboratory settings. Most participants indicated that formal STEM implementation remained limited despite general recognition of its value. Several respondents openly stated that teaching largely continued within conventional disciplinary structures because departmental organisation still separated subject areas.

Among participants who reported some degree of STEM-related teaching, four recurring pedagogical patterns emerged. The first pattern involved challenging exploratory problems. Some lecturers described beginning lessons with problems designed to stimulate inquiry and collaborative reasoning.

- *One Participant Explained:*

"You start with a difficult problem so that students begin thinking together and using what they know from different areas."

This reflects partial alignment with problem-based learning principles, although respondents rarely explained how such tasks were systematically designed or assessed.

The second pattern involved real-life problem orientation. Participants frequently argued that STEM teaching should focus on practical problems derived from everyday contexts.

- *A Lecturer Stated:*

"The problem must come from real life so that students can see why science, mathematics, and technology matter together."

However, several participants also noted that institutional subject separation made full integration difficult because some disciplinary combinations were not always available within the same teaching context.

The third pattern involved project-based learning. Several lecturers reported assigning projects requiring students to investigate practical problems over time.

- *One Focus Group Participant Noted:*

"Sometimes students do projects that look like STEM even when we do not formally call them STEM."

This suggests that fragments of STEM-compatible pedagogy may already exist informally within current practice, although without explicit conceptual structuring.

The fourth pattern involved hands-on practical activity. Participants consistently linked STEM education to practical engagement rather than purely theoretical instruction.

- *A Participant Explained:*

"Students must produce something visible and not just explain ideas verbally."

Despite this emphasis, no clear institutional evidence of STEM-generated artefacts was identified across the four institutions. No interdisciplinary prototypes, design models, technological products, or engineering outputs were observed during the study.

This absence became analytically significant because practical activity alone does not necessarily indicate integrated STEM if tasks remain discipline-specific and fail to generate visible interdisciplinary outputs.

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➢ *Institutional Factors Facilitating and Constraining STEM Implementation*

The third objective examined institutional conditions influencing STEM implementation within teacher education programmes. Two facilitating conditions emerged. The first was institutional potential for curricular innovation. Some participants argued that universities possess structural flexibility that could support STEM development because higher education institutions already function as sites of teaching experimentation and curriculum revision. The second was lecturer willingness to learn. Across institutions, participants consistently expressed readiness to receive STEM-related training.

- *One Lecturer Stated:*

"We are ready to learn because if STEM returns strongly, we must prepare teachers properly."

This willingness is analytically important because it indicates that resistance to reform is not the principal barrier.

At the same time, three major constraints dominated participant accounts.

The first and most frequently cited barrier was limited formal knowledge of STEM pedagogy. Many lecturers acknowledged broad awareness of STEM but limited understanding of how to organise interdisciplinary teaching systematically. The second barrier was weak institutional collaboration. Participants repeatedly referred to limited engagement with external STEM-supporting organisations such as national science institutions.

- *A Respondent Explained:*

"We do not collaborate enough with institutions that are already active in STEM."

The third barrier involved persistent disciplinary teaching structures. Participants consistently reported that subjects continue to be taught separately, making interdisciplinary lesson planning difficult.

- *One Lecturer Summarised this Challenge Directly:*

"Departments still operate independently, so integration becomes difficult even when lecturers support it."

➢ *Cross-Case Pattern*

Although all four institutions showed broad support for STEM education, differences emerged in confidence levels and pedagogical expression. Institutions with longer-established science education programmes tended to show stronger conceptual confidence, while institutions with smaller STEM teacher education structures more frequently reported uncertainty. However, the central pattern remained consistent across all sites: conceptual endorsement exceeded pedagogical maturity.

Taken together, the findings indicate that current teacher education practice contains early STEM-compatible elements, particularly practical work, project assignments, and problem-based tasks, but these elements remain fragmented and weakly institutionalised. Conceptual support for STEM exists, yet coherent interdisciplinary implementation remains underdeveloped.

V. DISCUSSION

The findings of this study reveal a structural contradiction that is increasingly documented across emerging STEM reform systems: teacher educators strongly endorse the value of STEM education, yet conceptual precision and pedagogical structures necessary for sustained implementation remain insufficiently developed. This contradiction is analytically important because teacher educators occupy a foundational position within educational reform systems. Their interpretations of STEM shape how future teachers understand curriculum integration (Kelley & Knowles, 2016; Ruggiero, 2022), how they organise classroom learning, and ultimately how Zambian national STEM national agenda, which is driven by the 2025 National Science, Technology and Innovation Policy and the 2023 curriculum framework is translated into practice. The findings therefore suggest that Zambia's earlier implementation difficulties may not have originated solely at school level, but may also reflect unresolved weaknesses within teacher preparation structures.

A central finding of the study is that conceptual understanding of integrated STEM education among teacher educators remains fragmented. Participants consistently described STEM through important pedagogical attributes such as student-centred learning, critical thinking, practical engagement, self-directed learning, and interdisciplinary awareness. Although these descriptors align with recognised dimensions of STEM pedagogy, they rarely appeared within a coherent explanatory model linking disciplinary integration, technological mediation, engineering reasoning, and structured problem solving into a unified instructional sequence. This pattern strongly supports the argument advanced by Bybee (2010) that educators frequently endorse STEM rhetorically while lacking operational clarity regarding what integrated STEM requires in actual teaching practice.

The findings further suggest that conceptual familiarity with STEM terminology may currently exceed pedagogical competence. Several participants initially rated themselves as having good or very good understanding, yet later struggled to explain how disciplinary integration should be enacted in teacher education classrooms. This divergence is analytically significant because it reflects a distinction between declarative awareness and operational understanding. Similar patterns have been identified by Margot and Kettler (2019) and Li et al., (2020) where educators often demonstrate confidence in STEM discourse without corresponding instructional clarity. In the present study, this indicates that confidence may currently be shaped more by policy exposure or educational rhetoric than by formal pedagogical preparation.

Another major contribution of the findings concerns disciplinary inheritance within university systems. Teacher educators are themselves products of strongly bounded academic disciplines, and these disciplinary traditions continue to shape how STEM reform is interpreted (Dubek, Rickey, & DeLuca, 2024). A mathematics educator may understand STEM primarily through modelling and quantitative reasoning, while a science educator may frame STEM through experimentation and laboratory practice. Without deliberate mechanisms connecting these disciplinary perspectives, lecturers naturally revert to subject-specific interpretations (Dare, Keratithamkul, Hiwatig, & Li, 2021; Liu, Aziku, Qiang & Zhang, 2024). Wren, Hetherington, Chappell, O'Kane, Sotiriou, Quacinella, ... & Duca, (2025) also supports the idea and empahsises deliberate institutional mechanisms connecting the disciplinary perspectives without which lecturers would naturally revert to subject-specific interpretations. This helps explain why several participants described STEM effectively within their own disciplinary area while remaining uncertain about broader interdisciplinary design.

The pedagogical findings reinforce this interpretation. Although participants identified exploratory problems, real-life tasks, project work, and hands-on activities as STEM-compatible teaching strategies, implementation remained inconsistent and largely informal. What emerges from the data is not the absence of innovative teaching altogether, but the absence of structured interdisciplinary design. Practical or student-active methods are present in some classrooms, yet these practices are rarely organised through explicit STEM integration logic such as expounded by Roehrig etal.(2021) and (Moore, 2010). This distinction is critical because practical teaching alone does not constitute integrated STEM unless multiple disciplinary forms of reasoning are intentionally coordinated around authentic problem solving.

The absence of STEM-generated artefacts across participating institutions is one of the strongest indicators that current implementation remains pedagogically incomplete. International STEM scholarship including Ong, Koh, Tan and Ng (2024) increasingly treats artefact production as a marker of integration maturity because design-based learning normally generates visible outputs such as prototypes, models, systems, experimental products, technological applications, or engineering responses. This perspective is grounded in the understanding that authentic integrated STEM experiences require students to produce tangible evidence of their interdisciplinary problem-solving (Ortiz-Revilla et al., 2022; Ong et al., 2024). Evidence published in literature such as Roehrig et al., (2021) suggests that where such artefacts are absent, STEM frequently remains conceptual rather than operational. In the present study, lecturers described project assignments and practical activities, yet no interdisciplinary products were observed This suggests that much practical engagement may still occur within conventional disciplinary teaching rather than within integrated STEM processes.

The findings also reveal that institutional organisation remains a major structural constraint. Participants repeatedly explained that subjects are taught separately, departments function independently, and opportunities for interdisciplinary lesson planning remain limited. This institutional separation directly undermines STEM implementation because integrated STEM requires coordinated planning, shared pedagogical ownership, and cross-disciplinary curriculum design. Similar findings are reported in Margot and Kettler (2019) showing that even where educators value STEM conceptually, weak collaboration frequently prevents meaningful implementation because institutional structures remain aligned to disciplinary independence rather than interdisciplinary problem solving. The barrier of limited collaboration identified in this study extends beyond internal university structures. Several participants referred specifically to weak interaction with external STEM-support institutions such as science centres and specialised educational agencies. In stronger STEM systems, collaboration among universities, science centres, industry, curriculum bodies, and schools often plays a decisive role in sustaining reform because such networks provide technical reinforcement, practical exposure, and pedagogical innovation pathways (Dieker, Butler, Ortiz, & Gao, 2021). The limited collaboration described by participants therefore suggests that teacher education institutions may currently be operating without sufficient external reinforcement for STEM development.

An important positive finding concerns lecturer willingness to learn. Despite conceptual limitations and pedagogical uncertainty, participants consistently expressed readiness to receive STEM-related training and strengthen instructional practice. This finding is highly significant because educational reform is often weakened more by resistance than by technical limitations. In this case, willingness appears stronger than preparedness, suggesting that institutional investment in carefully designed professional development could produce meaningful gains Recent large-scale STEM professional learning research such as by Sun, Du, Yao, & Rauduvaitė (2025) indicate that educators' willingness significantly improves the effectiveness of professional development when training focuses on practical pedagogical modelling rather than abstract policy explanation.

The findings also carry important implications for Zambia's competence-based education agenda. Competence-based education (MOE, 2023) and integrated STEM share important philosophical commitments, including application of knowledge, learner agency, contextual reasoning, and problem solving. However, competence-based reform cannot achieve intended outcomes if teacher educators remain uncertain about how integrated pedagogies function in practice. This creates a systemic risk in which policy alignment exists conceptually but remains operationally weak.

Viewed theoretically, the study suggests that STEM implementation in Zambia currently occupies an early developmental phase characterised by conceptual recognition without institutional consolidation. Teacher education institutions already contain fragments of STEM-compatible pedagogy, particularly practical work, project assignments, and exploratory tasks, but these fragments remain disconnected. The challenge therefore is not beginning from zero, but moving from fragmented pedagogical elements toward deliberate interdisciplinary integration supported by institutional redesign.

The findings therefore reinforce a growing conclusion within global STEM scholarship: successful STEM reform depends less on introducing new curriculum labels and more on transforming teacher educator knowledge systems, institutional collaboration structures, and pedagogical design cultures simultaneously.

VI. LIMITATIONS OF THE STUDY

Several limitations should be considered when interpreting the findings of this study. First, the study was conducted in four higher education institutions offering STEM-related teacher education programmes in Zambia. Although these institutions were purposively selected because of their strategic role in preparing secondary school teachers, the findings do not claim statistical representativeness across all teacher education institutions in the country. Institutional cultures, staffing patterns, and programme structures may differ in other universities and colleges not included in the study. The findings should therefore be interpreted as analytically transferable rather than statistically generalisable.

Second, the study relied primarily on self-reported accounts generated through questionnaires, interviews, and focus group discussions. While triangulation strengthened credibility, self-reported pedagogical descriptions may not always correspond fully with actual classroom practice. Some participants may have described intended or ideal pedagogical approaches rather than routine teaching behaviour. The absence of direct classroom observation therefore limits the ability to determine how frequently reported STEM-compatible strategies are enacted in actual teaching sessions.

Third, although the study identified the absence of STEM-generated artefacts across participating institutions, this conclusion was based on available evidence during field engagement rather than longitudinal institutional tracking. It remains possible that isolated interdisciplinary products may emerge within specific courses or projects that were not visible during the period of data collection. A longer observation period could provide deeper insight into how practical outputs develop over time within teacher education settings.

Fourth, the study focused specifically on teacher educators' conceptualisations and pedagogical accounts and did not include student teachers as a second analytical group. Including student teachers could have strengthened interpretation by showing whether teacher educator perspectives correspond with how future teachers actually experience STEM-related instruction during training.

Fifth, because STEM education remains a relatively recent and evolving policy discourse within the Zambian context, some conceptual uncertainty expressed by participants may partly reflect wider national policy fluidity rather than institutional weakness alone. This means that some conceptual gaps identified in the study may be influenced by broader reform conditions beyond individual lecturer competence.

Despite these limitations, the study provides important empirical insight because it addresses a level of STEM reform that remains underexplored in existing Zambian literature: the teacher education institutions where future STEM teaching capacity is formed. The multi-case design, triangulated data sources, and cross-institutional comparison strengthen the analytical value of the findings and provide a credible foundation for future research.

VII. FUTURE RESEARCH DIRECTION

Future studies should extend this work in three important directions. First, classroom observation studies are needed to examine how teacher educators translate stated STEM understanding into actual instructional practice. Second, longitudinal studies should investigate whether professional development interventions improve interdisciplinary teaching over time. Third, future research should include pre-service teachers to determine how STEM pedagogies experienced during training influence later classroom practice after graduation.

VIII. IMPLICATIONS FOR POLICY AND PRACTICE

The findings of this study generate important implications for educational policy, teacher education reform, and institutional practice in Zambia because they demonstrate that sustainable STEM implementation depends fundamentally on strengthening teacher educator capacity before wider curriculum expansion occurs. Although teacher educators widely recognise the strategic importance of STEM education, current conceptual and pedagogical readiness remains insufficiently consolidated to support large-scale interdisciplinary implementation. This suggests that future STEM reform should not begin primarily with renewed school-level curriculum rollout, but with systematic institutional preparation within teacher education where instructional identities and pedagogical routines are first formed.

A first policy implication concerns the urgent need for a nationally coordinated teacher educator development framework for integrated STEM education. The findings show that conceptual understanding among lecturers remains uneven and strongly shaped by individual disciplinary interpretation. Without a shared national framework, STEM education is likely to continue being interpreted differently across institutions, departments, and disciplines, thereby weakening implementation consistency. A national framework aligned with Zambia's competence-based education agenda would provide common conceptual language, pedagogical expectations, and implementation benchmarks for institutions preparing future teachers. Such a

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framework should define authentic interdisciplinary STEM practice, clarify the role of engineering and technology within teacher education, and specify expected forms of evidence for integrated learning.

A second implication concerns professional development design. The willingness expressed by participants to strengthen STEM competence provides a highly favourable starting point for reform. The findings in Wang, Moore., Roehrig., & Park's (2011) study support the idea that some levels of targeted professional development is required if STEM integration is to be sustainable. However, professional development must move beyond short awareness workshops toward sustained pedagogical modelling. The findings suggest that many lecturers already recognise STEM terminology but lack practical design competence. Effective professional development should therefore focus on interdisciplinary lesson design, problem-based pedagogy, engineering-oriented tasks, assessment of integrated learning, and production of STEM artefacts within teacher education contexts. Collaborative professional learning structures are likely to be especially effective because they allow lecturers from different disciplines to jointly design, test, and refine STEM teaching approaches over time.

A third implication concerns institutional restructuring within universities. Disciplinary separation emerged as one of the strongest barriers to STEM integration because subjects continue to be taught independently within departmental boundaries. Authentic STEM implementation therefore requires institutional mechanisms that actively support cross-disciplinary collaboration. Universities may need to establish interdisciplinary teaching clusters, shared curriculum planning teams, and joint pedagogical laboratories where science, mathematics, technology, and related lecturers co-design instructional activities. Without such structural adjustments, lecturers may continue interpreting STEM as an additional teaching philosophy rather than a collaborative instructional model.

A fourth implication concerns curriculum redesign within teacher education programmes themselves. Current teacher preparation already contains fragments of STEM-compatible pedagogy such as project work, practical assignments, and problem-based tasks, but these elements remain weakly integrated. Teacher education curricula should therefore include explicit interdisciplinary modules where pre-service teachers engage in structured design challenges, inquiry cycles, and collaborative problem solving linked to authentic contexts. Such modules should culminate in visible outputs because artefact production provides evidence that disciplinary knowledge has been applied in integrated ways. These outputs may include prototypes, design models, digital tools, agricultural innovations, or locally relevant engineering solutions.

A fifth implication concerns strengthening institutional partnerships beyond universities. The findings reveal limited collaboration between higher education institutions and external STEM-support organisations such as science centres and technical agencies. Stronger partnerships are necessary because STEM education develops more effectively when teacher preparation institutions operate within broader knowledge networks involving industry, research institutions, schools, and curriculum agencies. Such partnerships can provide practical contexts, technological exposure, and current innovation examples that enrich teacher education.

A sixth implication concerns assessment reform. Traditional teacher education assessment systems often reward content recall more than integrated problem solving. However, STEM education requires assessment approaches that recognise design thinking, collaborative reasoning, iterative improvement, and contextual application of knowledge. Teacher education institutions should therefore progressively incorporate interdisciplinary projects, design portfolios, reflective solution reports, and collaborative presentations into assessment systems.

A further implication concerns policy sequencing. Zambia's earlier STEM curriculum withdrawal demonstrates the risks of introducing reform before instructional systems are sufficiently prepared. The present findings suggest that future STEM implementation should follow a phased readiness model: teacher educator preparation first, institutional pilot implementation second, monitored school-level integration third, and broader expansion thereafter. Such sequencing reduces the likelihood of repeating earlier implementation difficulties.

Finally, the findings suggest that competence-based education policy already provides an important strategic platform for STEM reform. Many pedagogical principles embedded in competence-based education, including learner participation, practical application, contextual reasoning, and problem solving, align naturally with integrated STEM education. Rather than positioning STEM as an entirely separate reform, policy may achieve stronger results by treating STEM as an advanced implementation pathway within competence-based education itself.

Taken together, the findings indicate that Zambia's most strategic STEM investment lies not in immediate curriculum expansion, but in institutional strengthening of teacher education systems. When teacher educators develop conceptual clarity, interdisciplinary confidence, and practical design competence, future school-level STEM reform becomes substantially more sustainable.

IX. CONCLUSION

This study examined teacher educators' conceptualisations of Science, Technology, Engineering, and Mathematics education and the pedagogical practices through which STEM-related teaching is currently enacted in selected higher education institutions in Zambia. The findings demonstrate that although teacher educators strongly recognise the strategic value of STEM education for national development, innovation, and educational transformation, this recognition has not yet translated into sufficiently coherent interdisciplinary pedagogical practice within teacher education programmes. A central conclusion emerging from the study is that conceptual support for STEM education currently exceeds operational instructional readiness. Teacher educators commonly interpreted STEM through important pedagogical characteristics such as student-centred learning, critical thinking, practical engagement, self-directed learning, and interdisciplinary awareness, yet these elements were rarely organised into a coherent framework linking disciplinary integration, engineering reasoning, technological mediation, and structured problem solving. This conceptual fragmentation is significant because teacher educators serve as the primary pedagogical reference point through which future teachers acquire instructional habits and curriculum interpretations.

The study further demonstrates that STEM-compatible pedagogical elements already exist within teacher education practice, particularly through project work, practical assignments, exploratory tasks, and real-life problem orientation. However, these elements remain fragmented, weakly coordinated across disciplines, and insufficiently institutionalised. The absence of observable STEM-generated artefacts across participating institutions reinforces the conclusion that current practice remains at an early developmental stage of STEM implementation rather than representing mature interdisciplinary teaching. Institutional conditions help explain this pattern. Limited formal pedagogical knowledge of STEM, weak collaboration within and beyond institutions, and persistent disciplinary teaching structures continue to constrain implementation. At the same time, strong willingness among lecturers to strengthen STEM competence provides an important foundation for future reform. The study therefore concludes that the long-term success of STEM reform in Zambia depends fundamentally on strengthening teacher education before broader curriculum expansion is attempted. Sustainable STEM implementation requires conceptual clarity, interdisciplinary institutional structures, practical pedagogical modelling, and stronger collaboration between universities and external STEM-support systems.

At a broader level, the findings position teacher education institutions as the most strategic intervention point in Zambia’s STEM reform trajectory. These institutions are not merely sites of curriculum transmission, but the point at which STEM must first become pedagogically coherent before it can succeed nationally. Future research should therefore examine how targeted professional development, curriculum redesign, and institutional collaboration reshape teacher educators’ STEM practice over time. The evidence ultimately suggests that STEM reform becomes sustainable not when policy introduces new curriculum language, but when teacher educators themselves become confident interdisciplinary practitioners capable of modelling integrated learning for future generations of teachers.

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