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Fixing the leaky pipeline: curriculum misalignment and STEM transition barriers in South Africa – a convergent mixed-methods study

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Abstract. South Africa's Science, Technology, Engineering, and Mathematics (STEM) education pipeline continues to face critical attrition, particularly during the transition from secondary schooling to post-secondary engineering pathways. This study examines how subject streaming, especially the widespread placement of learners into Mathematical Literacy, affects preparedness for both Technical and Vocational Education and Training (TVET) and university-level engineering studies. Employing a convergent mixed-methods design within an interpretivist paradigm, the research integrated structured surveys, semi-structured interviews, and focus group discussions. Purposive and stratified sampling enabled representation across rural, peri-urban, and urban contexts, engaging 120 qualitative participants (policymakers, principals, and STEM lecturers) and 180 quantitative respondents (secondary learners, STEM teachers, and tertiary students). Thematic analysis identified five systemic challenges: (1) curriculum misalignment as a structural barrier, (2) curriculum tracking and exclusion through Mathematical Literacy, (3) teacher capacity deficits in STEM pedagogy, (4) institutional fragmentation and policy incoherence, and (5) persistent urban-rural inequalities in STEM access. Quantitative data corroborated these findings, with 72% of teachers reporting insufficient training and 63% of tertiary students indicating low preparedness for engineering studies. The study recommends systemic reforms, including vertical curriculum articulation, bridging programs, and sustained STEM teacher development, to reduce attrition and strengthen South Africa's STEM-to-engineering pipeline for the Fourth Industrial Revolution.

Keywords: STEM education, leaky pipeline, Mathematical Literacy, curriculum alignment, engineering readiness, teacher capacity, 4IR

1. Introduction and Background

Science, Technology, Engineering, and Mathematics (STEM) education is widely recognised as a critical driver of innovation, technological advancement, and socio-economic development, particularly in the era of the Fourth Industrial Revolution (4IR), which is reshaping labour markets through digitalization, automation, and artificial intelligence [13, 17]. Nations with robust STEM-to-engineering pipeline are better positioned to sustain competitiveness and address critical skills gaps. Yet, many systems continue to experience a "leaky pipeline", characterised by significant learner attrition at key transition points from secondary to tertiary education [11, 33].

In South Africa, this attrition is particularly pronounced in pathways leading to engineering and technology programs. Pure Mathematics participation declines sharply across the schooling pipeline, and only a small fraction of learners who begin it go on to engineering studies at Technical and Vocational Education and Training (TVET) colleges or universities [10]. The widespread placement of learners into Mathematical Literacy, often driven by shortages of qualified teachers, functions as a structural filter that constrains access to tertiary STEM opportunities [7, 32].

Persistent inequalities exacerbate these challenges. Rural and peri-urban schools frequently contend with underqualified teachers, inadequate infrastructure, and limited access to digital learning

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resources, reducing readiness for advanced STEM subjects [20, 26]. Teachers report insufficient training in 4IR-related pedagogies, including coding and robotics, which hampers their capacity to prepare learners for engineering studies [28, 30]. Consequently, first-year engineering courses exhibit high failure rates in calculus and physics, often exceeding 50% [14].

While policy frameworks such as CAPS, the White Paper on Science and Technology, and the Professional Development Framework for Digital Learning [9] emphasise STEM development, weak coordination between the DBE and the Department of Higher Education and Training (DHET) has resulted in fragmented implementation [6, 22]. Bridging initiatives and curriculum reforms remain localised, failing to resolve systemic barriers to progression.

Despite sustained policy attention, failure to address these structural leakages poses significant long-term risks. Persistent curriculum misalignment, restrictive subject streaming, and uneven teacher capacity are likely to worsen shortages of engineers and technical professionals. These skills are essential for infrastructure development, industrial growth, and technological innovation [41]. Within a knowledge-based economy, these systemic weaknesses constrain human capital formation and reduce national competitiveness in the Fourth Industrial Revolution.

Moreover, STEM attrition disproportionately affects learners from rural and low-income communities, reinforcing structural inequality and limiting socio-economic mobility [11, 35]. Without coordinated reform across the basic and post-school education sectors, the STEM-to-engineering pipeline will continue to reproduce inequitable outcomes and restrict broader participation in high-demand STEM careers [13, 26].

South Africa's education system faces a critical mismatch between high school STEM curricula and the competencies required for tertiary engineering programs. Disadvantaged learners are frequently streamed into Mathematical Literacy, limiting access to engineering pathways and reinforcing socio-economic inequities [4, 32]. Even students completing Pure Mathematics often struggle with abstraction, modelling, and problem-solving at university, with lecturers describing the transition to first-year engineering calculus as a "conceptual cliff", contributing to attrition rates exceeding 50% [21, 37]. Weak alignment between secondary and tertiary education, limited career guidance, and inadequate bridging programs, compounded by poor coordination between the DBE and DHET, fragment the STEM-to-engineering pipeline and constrain South Africa's capacity to develop the engineering workforce necessary for 4IR participation and national development goals [6, 25, 40].

Framed within the knowledge-based economy (KBE) perspective, the study investigates how effectively high school STEM curricula prepare learners for entry into engineering pathways at TVET colleges and universities, addressing the persistent "leaky pipeline" where learners drop out at critical transition points [31, 41]. The research emphasises curriculum misalignment, restrictive subject streaming, teacher capacity deficits, and weak institutional coordination as systemic barriers to progression [9].

The overarching aim of this study is to examine how curriculum alignment, subject streaming practices, teacher preparedness, and institutional coordination within South Africa's STEM education system shape learner preparedness for transition into post-school engineering pathways at TVET colleges and universities.

Accordingly, the study is guided by the following objectives:

1. To analyse the alignment between secondary STEM curricula and the entry requirements of tertiary engineering programs.

2. To examine stakeholder perceptions of curriculum preparedness, subject streaming, and transition challenges.

3. To identify systemic, instructional, and policy-level barriers that constrain learner progression into engineering studies.

4. To propose evidence-based reforms to strengthen STEM transitions and reduce attrition in engineering pathways.

Employing a convergent mixed-methods design, the study combines surveys, semi-structured interviews, and focus groups with 350 stakeholders to generate comprehensive insights [5, 18]. Preliminary data indicate that 72% of teachers report insufficient training in digital and 4IR-related STEM content, while 63% of tertiary students feel underprepared for engineering programs [23, 40], underscoring the urgency of systemic reform, curriculum articulation, and coordinated interventions to enhance STEM readiness and national competitiveness. Qualitative data provide insight into these patterns, revealing how limited training opportunities, resource constraints, and uneven professional development contribute to low confidence and gaps in instructional delivery.

2. Literature review

Curriculum alignment across educational levels is a critical determinant of student success in STEM. In South Africa, the absence of vertical alignment between the high school curriculum and tertiary engineering requirements results in persistent under-preparedness [6]. The CAPS framework streams learners into Pure Mathematics or Mathematical Literacy from Grade 10, a structural decision that profoundly shapes post-school opportunities. Placement in Mathematical Literacy effectively blocks entry into engineering programs, reinforcing inequities rooted in school resourcing and teacher shortages [32, 33]. International evidence shows that countries with strong curriculum articulation, such as Singapore and Finland, reduce STEM attrition by ensuring continuity between secondary and higher education [16, 29]. South Africa's lack of a coordinated articulation strategy thus constitutes a systemic gap.

Subject streaming is one of the most widely recognised barriers in the STEM-to-engineering pipeline. Studies show that learners from under-resourced schools are disproportionately placed in Mathematical Literacy, often without sufficient career guidance, reducing their chances of accessing engineering programs [4]. This practice prioritizes institutional performance targets over learner potential, creating a policy loophole that entrenches exclusion [32]. Globally, similar patterns of early academic tracking restrict disadvantaged learners' access to advanced mathematics and technical careers [11]. The South African case demonstrates how systemic constraints intersect with inequality to reproduce exclusion in engineering fields.

The preparedness of STEM teachers is central to learner outcomes, yet many South African educators report limited training in advanced mathematics and emerging 4IR content such as coding and robotics [28, 30]. Teacher shortages are especially acute in rural schools, where non-specialists are often assigned to mathematics and science [29]. Even where policies mandate continuous professional development, delivery is uneven, with rural teachers citing poor access and superficial workshops [21]. This contributes to a disconnect between rote-based teaching in high schools and inquiry-driven pedagogies in tertiary engineering programs [37]. International comparisons show that integrated teacher development and collaborative STEM teaching networks can narrow these gaps [16], but such systemic support is weak in South Africa.

Beyond classrooms, systemic fragmentation weakens the STEM-to-engineering pipeline. Weak collaboration between the DBE and the DHET means that secondary and tertiary curricula evolve in silos, limiting articulation [12]. Learners experience abrupt shifts in expectations between high school and university, contributing to high failure rates in first-year engineering courses [19]. While bridging programs exist, they are implemented inconsistently and lack national coordination [27]. The absence of a formal articulation framework or shared benchmarks between DBE and DHET is a major structural gap.

Persistent inequalities compound these barriers. Learners in rural and peri-urban schools report limited access to laboratories, ICT infrastructure, and qualified teachers, leaving them underprepared for tertiary STEM programs [17, 20]. The digital divide further restricts access to resources that support mathematics learning, while urban schools increasingly integrate robotics and coding into their curricula [26]. UNESCO [2024] confirms that without targeted resource allocation, systemic disparities will continue to undermine equity in STEM transitions.

STEM education literature increasingly conceptualises learner progression as a systemic pipeline linking secondary schooling to post-school engineering and technical pathways, with significant attrition occurring at key transition points. In South Africa, this leaky pipeline is shaped by curriculum structures, subject streaming, teacher capacity, and weak institutional coordination, all of which influence learner readiness and persistence in STEM fields [4, 11]. Inadequate curriculum alignment between secondary mathematics and science and the epistemic demands of tertiary engineering programmes undermines preparedness and contributes to high first-year failure and dropout rates [6, 37]. Subject streaming through Mathematical Literacy functions as a structural barrier, disproportionately limiting access to engineering pathways for learners in rural and under-resourced contexts [20, 32]. These challenges are compounded by shortages of qualified teachers and limited pedagogical and digital capacity, constraining effective curriculum enactment [28, 30]. Collectively, weak STEM-to-engineering pipelines undermine human capital development and inclusive participation in knowledge-based economies, with implications for innovation and national competitiveness [13, 40, 41].

Despite extensive research on STEM education in South Africa, key gaps persist. Most studies treat curriculum misalignment and subject streaming as isolated issues rather than interconnected systemic challenges affecting engineering pathways [6, 7]. Additionally, research often focuses separately on secondary or tertiary education, with limited attention to the full STEM-to-engineering pipeline and learner trajectories, leaving school-level reforms and university bridging programs insufficiently connected [27]. Stakeholder perspectives, particularly of learners and lecturers, are underrepresented, constraining understanding of how policy and structural decisions shape lived experiences and first-year preparedness [19, 21, 28]. Finally, few studies link STEM-to-engineering pipeline dysfunction to national competitiveness within the Knowledge-Based Economy, leaving the relationship between curriculum misalignment, human capital development, and 4IR readiness underexplored [40, 41]. Addressing these gaps is essential to enhance engineering capacity and equitable participation in South Africa's knowledge-driven economy.

3. Theoretical frameworks

This study is underpinned by systems theory and the KBE framework, which offer a lens to examine curriculum misalignment, institutional fragmentation, and teacher preparedness in shaping learner transitions into engineering pathways [21].

Systems theory conceptualizes education as an interconnected system where curriculum, governance, teacher training, and socio-economic context interact, with weaknesses in one area cascading into broader dysfunctions [3, 23]. Within this study, three interdependent subsystems are central:

1. *Curriculum and pedagogy* – misalignment between high school mathematics and science content and tertiary engineering requirements creates "cognitive cliffs" [6, 37].
2. *Institutional coordination* – poor articulation between the DBE and DHET results in fragmented STEM transitions [22].
3. *Socio-economic context* – inequities in infrastructure, teacher deployment, and digital access constrain participation [34].

The KBE framework links education to national development by emphasising knowledge production and human capital in the 4IR [35, 41]. It highlights:

1. *Human capital formation* – weak mathematics preparation reduces engineering eligibility [31, 40].
2. *Innovation capacity* – STEM attrition weakens technological advancement [25, 29].
3. *Equity and inclusion* – streaming policies disadvantage under-resourced learners [13, 32].

Integrating systems theory and KBE frames STEM leakages as systemic dysfunctions with long-term developmental consequences, underscoring the urgency of curriculum reform, teacher development, institutional collaboration, and equitable resource allocation [16, 20].

4. Methodology

This study adopted a convergent mixed-methods design, in which quantitative and qualitative data were collected concurrently, analysed independently, and integrated during the interpretation phase [8, 38]. Quantitative data were used to identify systemic patterns related to subject streaming, learner preparedness, and access to post-school engineering pathways, while qualitative data generated contextualised insights into stakeholder experiences, institutional practices, and structural constraints shaping these patterns. Integration occurred through narrative meta-inference, whereby qualitative themes were systematically used to explain, contextualise, and deepen interpretation of quantitative findings [8]. For example, quantitative results indicating high proportions of learners reporting inadequate preparedness and restricted progression into engineering pathways were interpreted alongside qualitative accounts highlighting curriculum misalignment, Mathematical Literacy streaming, and teacher capacity constraints as underlying mechanisms [12, 36]. Although no formal joint display was constructed, convergence and divergence across data strands were examined during the discussion of findings to enhance triangulation and explanatory depth, consistent with established mixed-methods practices in education research [38].

4.1. Target population and sampling

The target population comprised two primary groups, as illustrated in table 1 below: STEM learners across high schools, TVET colleges, and universities, and education professionals involved in curriculum delivery, institutional leadership, and policy implementation, including teachers, lecturers, principals, and policymakers. Secondary participants included curriculum designers and policy implementers engaged in STEM education reform. A combination of purposive and stratified sampling was employed to ensure representation across institutional roles and urban, peri-urban, and rural contexts, consistent with mixed-methods research conventions [8].

Table 1
Summary of study participants ($n = 360$).

Data type	Participant group	Subgroup	*n*
Qualitative	Policymakers	National / Provincial	10
Qualitative	High school principals	Public schools	10
Qualitative	TVET / University principals	Institutional leadership	10
Qualitative	TVET lecturers	Engineering & STEM	40
Qualitative	University lecturers	Engineering & STEM	50
Subtotal (Qualitative)			**120**
Quantitative	High school STEM learners	Grades 10-12	180
Quantitative	TVET / University engineering students	Undergraduate	20
Quantitative	STEM teachers	Secondary schools	40
Subtotal (Quantitative)			**240**
Total Participants			**360**

For the qualitative component, purposive sampling was used to select information-rich participants with direct experience of STEM curriculum design, subject streaming, and post-school transitions. The qualitative sample comprised 120 respondents, including 10 policymakers (ADM1-ADM10), 10 high school principals (PR1-PR10), 10 TVET and university principals (PR11-PR20), and 10 focus groups involving 40 TVET lecturers (LEC1-LEC40) and 50 university lecturers (LEC41-LEC90). Sample sufficiency was guided by principles of thematic saturation and cross-stakeholder triangulation rather than statistical representativeness [38].

For the quantitative component, stratified sampling was applied to ensure representation across learner groups and educational contexts. Power analysis informed the quantitative sample size, targeting 0.80 statistical power at a 95% confidence level. The quantitative sample comprised 180 high school STEM learners (HSS1-HSS180), 20 TVET and university engineering students (TVS1-TVS20), and 40 STEM teachers (HST1-HST40). Gender, subject specialisation, and geographic diversity were considered to reduce sampling bias and enhance the generalisability of the statistical findings [8].

Sample sufficiency for the qualitative component was guided by principles of thematic saturation and cross-stakeholder triangulation, while quantitative sample sizes were informed by power analysis targeting 0.80 statistical power at a 95% confidence level [8, 38].

4.2. Data collection instruments and procedures

This subsection outlines the procedures through which the qualitative and quantitative instruments were administered. It details participant recruitment strategies, consent processes, data collection timelines, and the practical administration of interviews, focus groups, and surveys across school, TVET, and university sites. Separating instrument design from data collection procedures ensures methodological clarity by distinguishing what data were generated from how data were collected and managed, in line with established mixed-methods research conventions [8, 18].

4.2.1. Qualitative instruments

Semi-structured interviews were conducted with 20 higher education lecturers, five TVET administrators, and five policymakers (POL1-POL5). The interview protocol combined thematic consistency with flexibility, following best practice in qualitative inquiry [38]. Interview questions were clustered around:

1) curriculum readiness, examining the adequacy of high school STEM preparation for engineering studies [23, 36];

2) subject streaming, exploring the impact of Mathematical Literacy versus Pure Mathematics placement [7, 10];

3) transition barriers, identifying systemic obstacles in progression to tertiary STEM programmes [12, 27];

4) reform suggestions, gathering stakeholder recommendations [16, 21].

Ten learner focus groups ($n = 80$) employed scenario-based prompts to elicit peer perspectives on STEM preparation and transition experiences [15, 30]. Instrument design was informed by literature on curriculum alignment and learner transitions and validated through expert review and pilot testing [17, 38].

4.2.2. Quantitative instruments

A structured questionnaire was administered to 180 high school learners, 40 STEM educators, and 20 first-year engineering students. It measured:

1) *demographics* – school type, location, and subject choices to identify systemic disparities across rural and urban contexts [2, 34];

2) *STEM learning experiences* – access to laboratories, digital tools, and qualified teachers as predictors of learner outcomes [4, 19];

3) *transition preparedness* – perceived readiness for tertiary STEM studies using validated Likert-scale items [1, 25];

4) *curriculum perceptions* – alignment of school content with tertiary engineering assessed via closed and open-ended questions [9, 11].

Validity and reliability were ensured through expert panel review and pilot testing, with Cronbach's alpha exceeding 0.70 across all scales. Questionnaires were distributed digitally and in print to ensure accessibility in contexts of digital inequality [21, 23].

4.3. Data analysis

Qualitative data from interviews and focus groups were transcribed verbatim and analysed using Braun and Clarke's [5] six-phase thematic analysis, supported by NVivo 14 for systematic coding and management [36].

Step 1: Initial coding involved descriptive labels such as *"teachers not trained in robotics"* or *"Mathematical Literacy closes doors"*, clustered into provisional categories [1, 7].

Step 2: Theoretical mapping applied systems theory and KBE frameworks:

- *Systems theory*: curriculum and pedagogy [37], institutional coordination [22], socio-economic context [20].
- *KBE*: human capital formation [31], innovation capacity [25], equity and inclusion [13].

Step 3: Theme development consolidated categories into higher-order themes – curriculum misalignment, exclusion via Mathematical Literacy, teacher capacity gaps, institutional fragmentation, and urban-rural inequities [2, 15, 17, 33].

Step 4: Rigor and triangulation was ensured through peer debriefing, inter-coder checks, audit trails, and thematic saturation, supported by survey data indicating 63% under-preparedness [23, 38].

The quantitative component utilised a structured survey administered to learners, teachers, and post-school students, with items measured on five-point Likert scales ranging from 1 (strongly disagree) to 5 (strongly agree), consistent with established educational research practice [8]. Survey items assessed perceptions of curriculum preparedness, access to STEM resources, instructional support, and readiness for post-school STEM study. Data analysis was conducted using SPSS v28 and included descriptive statistics alongside inferential techniques such as Chi-square tests and analysis of variance (ANOVA) to examine differences across educational levels and geographic contexts [4, 10]. Where significant differences were observed, post-hoc analyses were performed to identify group-level variation. Construct validity was established through factor analysis, while internal consistency was confirmed using Cronbach's alpha coefficients exceeding 0.70 [11, 39]. Key constructs, including learner preparedness, were operationalised through composite indices, ensuring conceptual alignment with the study's framework. Integration with qualitative findings revealed convergent evidence of systemic gaps in STEM transitions and 4IR readiness [25, 27, 36].

4.4. Ethical considerations

Ethical clearance was granted by UNISA's Research Ethics Committee (Ref: 2021/05/12/57643482/19/am). Informed consent was obtained from adult participants and assent from minors alongside parental consent. Confidentiality was maintained through anonymised codes (e.g., HSS1, TVL3), and all data were securely stored in password-protected formats. Procedures adhered to both national and international research ethics standards [12].

4.5. Rigor and validity

Rigor was ensured across qualitative and quantitative strands through established criteria. In the qualitative component, credibility was strengthened via triangulation and member checking, transferability through thick contextual descriptions, dependability via audit trails, and confirmability through reflexive journaling [24]. Quantitative rigor was maintained through expert instrument review, pilot testing, Cronbach's alpha for reliability, and monitoring response rates to ensure internal validity [5].

The convergent mixed-methods design within an interpretivist paradigm enabled comprehensive exploration of systemic, curricular, and pedagogical challenges in South Africa's STEM-to-engineering pipeline [18]. Stratified purposive sampling, validated survey instruments, and robust thematic and statistical analyses produced context-sensitive insights from learners, educators, and policymakers [26, 28]. This methodological rigor underpins the subsequent presentation of findings, integrating thematic patterns, quantitative relationships, and cross-sectoral perspectives to illuminate the multifaceted factors influencing post-secondary STEM transitions [6].

5. Discussion of findings

The convergent mixed-methods design enabled not only triangulation of findings but also the development of meta-inferences linking statistical patterns to underlying institutional and pedagogical mechanisms. This approach provides a more comprehensive explanation of STEM transition challenges than would be possible through a single-method design, as it integrates breadth of patterns with depth of contextual understanding [8, 15, 38].

This section presents the empirical findings of the study using an integrated mixed-methods design to examine systemic challenges shaping STEM-to-engineering transitions in South Africa. Although the wider study generated extensive evidence on general STEM pathways, the analysis focuses specifically on the curriculum-to-engineering pipeline to ensure analytical coherence and theoretical depth. Informed by systems theory and the KBE framework, STEM progression is conceptualised as a multi-level process shaped by curriculum alignment, institutional practices, and human capital development [35, 41].

Findings are presented thematically, drawing on patterns identified through iterative coding, theoretical mapping, and narrative integration of survey and interview data. Quantitative analyses establish the scale and distribution of challenges related to access, curriculum alignment, and learner preparedness across educational contexts, while qualitative findings illuminate the institutional and pedagogical mechanisms through which these challenges manifest in schools, TVET colleges, and universities. Each theme is substantiated using anonymised participant quotations from learners (HSS), principals (PR), TVET lecturers (TVL), policymakers (POL), and university administrators (ADM), alongside relevant quantitative indicators. This integrative analytical approach enables triangulation, enhances validity, and supports theory-informed interpretation of systemic constraints within the STEM-to-engineering pipeline [8, 15].

Although statistically significant relationships were identified between subject streaming, curriculum alignment, and learner preparedness, these are interpreted as associative patterns rather than causal effects, consistent with the study's interpretivist epistemological orientation [8, 11].

5.1. Theme 1: Curriculum misalignment as a structural barrier

A recurring concern across participants was the systemic misalignment between high school STEM curricula and the epistemic and applied demands of tertiary engineering programmes. Survey data revealed that 63% of first-year engineering students reported feeling underprepared for the mathematical and technical demands of their programmes, despite passing high school mathematics and physical science. This quantitative pattern is further explained by qualitative accounts highlighting exam-oriented pedagogy and weak curriculum articulation, which collectively undermine applied problem-solving readiness. Similarly, 58% of teachers acknowledged that the curriculum does not adequately develop applied problem-solving skills required in engineering contexts [10, 31].

Learners framed this misalignment as a shift from assessment-driven instruction to application-oriented learning. One student reflected:

> We were taught to pass exams, not to understand concepts. When I got to engineering, the way they teach is completely different, and I felt lost from day one. (TVS14)

Teachers corroborated this pedagogical gap. One noted:

> The curriculum is overloaded with content, but it does not prepare learners for application. They arrive at university with theory, but not the ability to solve practical engineering problems. (HST6)

Qualitative evidence therefore contextualises the statistical trend by showing how assessment-driven instruction and limited emphasis on conceptual understanding translate into difficulties in applying knowledge within engineering contexts.

Institutional actors attributed this misalignment to systemic pressures. A principal explained,

> Schools are under pressure to deliver matric pass rates, so teachers teach to the exam. But universities want critical thinking and application, which are not measured in matric assessments. (PR2)

At the policy level, a DBE-DHET disconnect was emphasised:

> Curriculum frameworks are not informed by higher education requirements. There is little dialogue between departments, so we keep producing learners who are not ready for engineering studies. (POL3)

These findings are summarised in table 2.

Table 2
Reported curriculum misalignment in STEM transitions ($n = 220$).

Stakeholder group	Reported challenge	%
First-year engineering students	Felt underprepared for university STEM demands	63%
STEM teachers	Curriculum does not prepare learners for applied problem-solving	58%

This pattern indicates a breakdown in alignment between curriculum content and the applied demands of tertiary engineering education, contributing directly to learner under-preparedness. By prioritising assessment performance over conceptual understanding, the system produces learners who meet formal requirements but lack the problem-solving competencies required in engineering contexts. This misalignment ultimately constrains effective progression within the STEM-to-engineering pipeline and limits the development of applied technical skills necessary for engineering pathways [37]. From a KBE perspective, curriculum misalignment constrains human capital formation by limiting learner readiness for innovation-driven sectors [4, 11]. These findings align with international and South African literature identifying weak curriculum articulation as a critical STEM-to-engineering pipeline disruption point, increasing early academic difficulty and attrition in engineering programmes [6, 16, 36].

Qualitative evidence therefore contextualises the statistical trend by showing how assessment-driven instruction and limited emphasis on conceptual understanding translate into difficulties in applying knowledge within engineering contexts.

5.2. Theme 2: Curriculum tracking and structural exclusion through Mathematical Literacy

Building on the broader issue of curriculum misalignment, this theme examines how subject streaming through Mathematical Literacy reinforces structural exclusion within the STEM-to-engineering pipeline. Survey data revealed that 46% of learners ($n = 82$ of 180) were placed in Mathematical Literacy, despite 78% of these learners aspiring to STEM-related careers. In contrast, 92% of learners enrolled in Pure Mathematics indicated interest in STEM fields, demonstrating how subject tracking systematically restricts access to engineering pathways [2, 17]. Qualitative findings help explain this distribution, revealing institutional pressures such as teacher shortages, resource constraints, and performance-driven streaming practices that shape subject placement decisions. These patterns are illustrated in figure 1. Qualitative narratives further illuminate this distribution by showing how school-level decision-making, often driven by resource limitations, reinforces these statistical patterns.

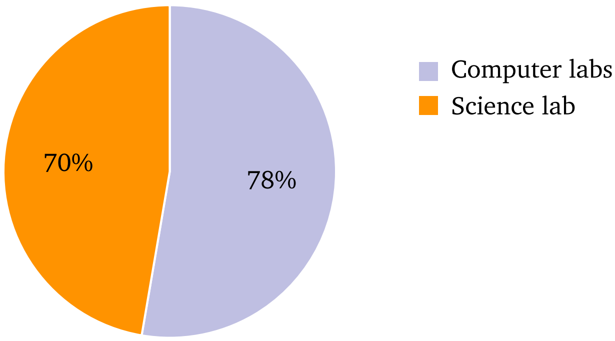

Figure 1: Distribution of learners by subject placement ($n = 180$).

Stakeholder narratives exposed the institutional drivers of such placement. A principal admitted, "Literacy is promoted to boost school results" (PR3), while a teacher revealed, "All our learners were placed in Literacy because we had no Pure Maths teacher" (HST8). Quantitative analysis reinforced these accounts, showing that schools reporting mathematics teacher shortages had significantly higher rates of Mathematical Literacy placement [19].

Learners described the exclusionary consequences of early streaming. One reflected, "I didn't know it meant I couldn't do engineering" (TVS6), while another stated, "By the time I understood the consequences, it was too late to switch" (TVS11). These experiences align with national findings that early subject tracking disproportionately affects disadvantaged schools and learners [4, 10].

The cumulative impact of streaming is further illustrated in table 3, which demonstrate pronounced disparities in STEM aspirations by subject stream.

Table 3
Relationship between subject stream and STEM career aspirations ($n = 180$).

Stream	Learners (n)	Interested in STEM (%)
Mathematical Literacy	82	78%
Pure Mathematics	98	92%

From a systems theory perspective, Mathematical Literacy streaming reflects a breakdown in institutional coordination, whereby schools prioritise short-term performance indicators over long-term learner progression [3, 14]. Within the KBE framework, this form of exclusion diminishes human capital formation and constrains national innovation capacity [35]. The convergence of quantitative patterns and qualitative accounts indicates that Mathematical Literacy functions as a structural gatekeeping mechanism within the STEM-to-engineering pipeline, reproducing unequal access to high-status engineering trajectories, particularly for learners from rural and low-income contexts [26, 35].

The convergence between statistical evidence of restricted access and qualitative accounts of institutional decision-making indicates that Mathematical Literacy functions as a systemic gatekeeping mechanism rather than a neutral curricular alternative.

5.3. Theme 3: Teacher capacity and pedagogical gaps in STEM preparation

Extending beyond curriculum structures, this theme focuses on teacher capacity as a key factor shaping the quality of STEM preparation. This finding addresses Research Questions 1 and 3 concerning systemic and instructional barriers. Survey results revealed that 72% of teachers reported lacking training in digital and 4IR-related STEM content, while 68% admitted limited confidence in teaching advanced mathematical concepts [13, 23].

Figure 2 illuminates the distribution of teacher-reported challenges, highlighting the predominance of digital skills deficits and low confidence in handling advanced STEM topics [28].

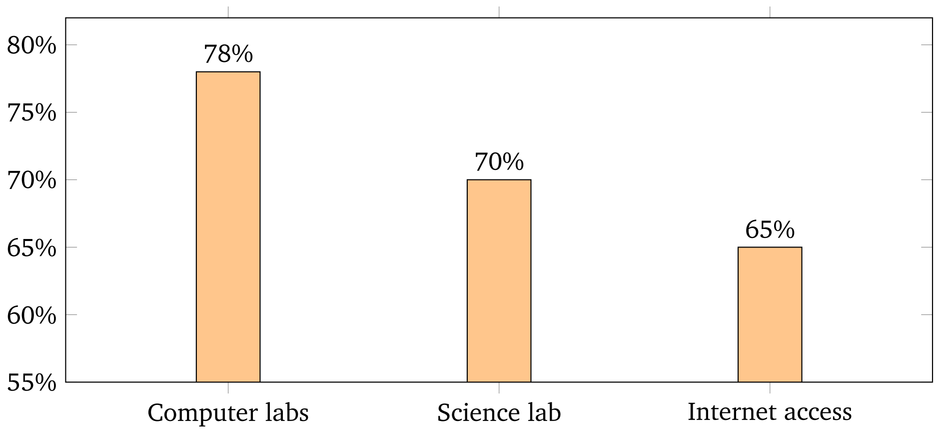

Figure 2: Teacher-reported STEM teaching challenges ($n = 40$).

Educators candidly acknowledged these limitations. One high school teacher explained, “We are teaching coding on paper because there are no laptops” (HST12), while another admitted, “I am not trained for robotics or advanced calculus, so I skip those topics” (HST9). Such testimony was echoed at tertiary level: a university lecturer noted, “The gap begins with underprepared teachers who rely on rote methods” (LEC 7). These qualitative accounts contextualise the quantitative findings by illustrating how capacity constraints manifest in everyday teaching practices, including topic omission and reliance on rote methods.

Policymakers acknowledged the systemic roots of these gaps, attributing them to uneven teacher professional development programs and poor alignment between DBE and DHET training mandates (POL2). This aligns with recent research showing that fragmented teacher upskilling perpetuates inequities in learner outcomes [7, 36].

Learners also recognised the consequences. One student lamented, “My teacher told us to just memorize the formulas; when we got to university, I didn’t know how to apply them” (TVS21). Another added, “We had no exposure to lab work, so the first time I used proper equipment was at varsity” (TVS9). Such accounts underscore the pedagogical gaps that hinder critical thinking, inquirybased learning, and practical engagement [15, 21]. This alignment between learner experiences and teacher-reported limitations reinforces the interpretation that pedagogical gaps are systemic rather than isolated classroom issues.

These findings highlight teacher capacity as a central factor shaping the effectiveness of STEM instruction and learner preparedness. Where teachers lack subject depth, pedagogical support, or exposure to applied and digital competencies, curriculum intentions are not fully realised in practice [2, 35]. This results in a disconnect between what is taught and the skills required for engineering study, ultimately limiting learner progression and reinforcing systemic inequities in STEM outcomes [29, 41].

5.4. Theme 4: Institutional fragmentation and policy misalignment in STEM transitions

A fourth theme emerging from the study is the institutional fragmentation between schools, TVET colleges, and universities, compounded by misaligned policy frameworks between the DBE and the DHET. This directly addresses Research Question 3 on systemic barriers to STEM transitions.

Survey results showed that 58% of lecturers and TVET administrators reported inadequate communication channels between secondary and tertiary institutions, while 64% of policymakers acknowledged overlapping or conflicting mandates between DBE and DHET [10, 20]. This fragmentation undermines coherent learner progression, leaving many students underprepared despite completing the National Senior Certificate. Qualitative findings deepen this understanding by revealing how weak communication channels, policy silos, and limited collaboration between institutions contribute to these reported challenges.

Table 4 demonstrate these stakeholder perspectives, showing that most participants perceived institutional and policy misalignment as a major obstacle to effective STEM transitions.

Table 4
Stakeholder perceptions of institutional and policy misalignment in STEM transitions ($n = 70$).

Stakeholder group	Reported institutional misalignment (%)	Reported policy misalignment (%)
TVET administrators ($n = 15$)	60%	53%
University lecturers ($n = 20$)	55%	62%
Policymakers ($n = 10$)	64%	64%
High school principals ($n = 25$)	52%	47%

Qualitative findings provided depth to these statistics. A TVET lecturer remarked, “We never get proper handover information about learners’ preparedness, schools just send them on” (TVL7). A university administrator echoed this sentiment: “Policies are written in silos; DHET and DBE rarely coordinate on bridging programs” (ADM4). Policymakers themselves admitted systemic challenges, with one conceding, “Sometimes DBE promises reforms without consulting DHET, and implementation falls apart” (POL4).

From the learner perspective, this fragmentation translates into tangible struggles. One student noted, “We passed matric but when we arrived at varsity, we were told we lacked the prerequisites” (TVS14). Another lamented, “The systems don’t speak to each other, and we are the ones who suffer” (TVS20). These voices illustrate how institutional silos and inconsistent bridging programs weaken the education pipeline.

Within a systems theory framework, fragmentation reflects a breakdown in the interconnections of subsystems, disrupting knowledge flows and learner progression across school, TVET, and university sectors [3, 37]. From a KBE perspective, such systemic disjuncture undermines long-term innovation potential by failing to cultivate human capital effectively [9, 13]. The absence of strong feedback loops and collaborative planning mechanisms further compromises transition coherence, reflecting a coordination failure that limits the impact of policy interventions designed to strengthen STEM progression [11, 12].

The convergence of quantitative perceptions of misalignment and qualitative accounts of systemic disconnection indicates a breakdown in inter-institutional coordination that undermines coherent STEM progression.

5.5. Theme 5: Structural inequalities in STEM access: the urban-rural divide

A central theme identified in this study is the entrenched socio-economic and geographical inequality that shapes STEM participation in South Africa, particularly disadvantaging learners in rural and under-resourced areas. This theme directly addresses research questions 3 and 4 on systemic barriers and potential interventions.

Quantitative data highlighted stark disparities between urban and rural schools in terms of resource availability. As shown in table 5, 78% of urban learners reported access to functional computer labs compared to only 32% of rural learners. Similarly, access to science laboratories was reported by 70% of urban learners but only 46% of rural learners. Internet access displayed the widest gap, with 65% of urban learners having reliable access versus just 28% of rural learners [26, 34]. These findings underscore the structural inequities that compromise learner preparedness for higher-level STEM engagement.

Table 5
Reported access to STEM resources: urban vs rural contexts ($n = 180$).

Resource type	Urban learners with access (%)	Rural learners with access (%)
Computer labs	78%	32%
Science lab	70%	46%
Internet access	65%	28%

Qualitative findings provide important context for these disparities, illustrating how resource limitations, infrastructure gaps, and uneven teacher distribution shape learners' day-to-day STEM experiences.

Qualitative findings reinforced these quantitative patterns. Learners in rural schools described severe limitations: "We don't have a computer lab" (HSS9), while a teacher added, "We improvise experiments with bottles and string" (HST10). Another educator contrasted contexts starkly: "In the city they teach robotics; here we don't even have chalk" (HST4). A principal lamented, "Our lab was donated but never connected to the internet" (PR10). Students articulated how these disparities shaped aspirations: "We don't dream big because our school doesn't have the resources" (HSS18). University lecturers echoed this, observing that rural learners arrive "with huge deficits in basic lab exposure, making first-year practicals overwhelming" (LEC11).

These narratives contextualise the statistical differences by showing how resource inequality translates into constrained learning opportunities and reduced exposure to practical STEM engagement.

These disparities reflect deeply embedded structural inequalities that shape access to STEM learning opportunities across contexts. Limited infrastructure, uneven teacher distribution, and restricted access to digital resources collectively constrain learner preparedness and participation in engineering pathways [22]. Without targeted and sustained intervention, these inequalities will continue to reproduce uneven outcomes within the STEM-to-engineering pipeline and limit broader participation in knowledge-driven sectors [27, 35].

While the quantitative findings indicate high proportions of learners experiencing inadequate preparedness and restricted access to engineering pathways, the qualitative data complicate these patterns by revealing how curriculum misalignment, subject streaming practices, and uneven teacher capacity operate as underlying causal mechanisms rather than isolated learner deficits [14]. This convergence between quantitative disparities and lived experiences suggests that structural inequality operates as a foundational constraint across the STEM-to-engineering pipeline rather than an isolated contextual factor.

Bridging these gaps requires targeted ICT investment, equitable teacher deployment, and resource reallocation to underserved schools. Recent scholarship emphasises that interventions must move beyond infrastructure donations to sustainable integration of digital tools, ongoing teacher development, and systemic policy coordination [19, 33].

5.6. Integrated meta-inference summary

Across all themes (table 6), a consistent pattern of convergence emerges between quantitative and qualitative data strands. Statistical evidence of learner under-preparedness, restricted access to STEM pathways, teacher capacity deficits, institutional fragmentation, and resource inequality is systematically explained by qualitative insights into pedagogical practices, institutional constraints, and policy misalignment.

Table 6
Major themes and subthemes in STEM transition barriers.

Major theme	Subtheme 1	Subtheme 2	Subtheme 3	Supporting authorities
1. Curriculum misalignment as a structural barrier	Misalignment between high school and tertiary curricula	Assessment-driven teaching vs applied reasoning	Learner underpreparedness for calculus and problem-solving	[2, 17, 31]
2. Curriculum tracking and structural exclusion through Mathematical Literacy	Forced streaming into Mathematical Literacy	Policy loopholes and administrative rigidity	Long-term exclusion from STEM and engineering careers	[14, 33, 34]
3. Teacher capacity and pedagogical gaps in STEM preparation	Lack of 4IR/digital readiness among teachers	Reliance on rote-based instruction	Inadequate professional development opportunities	[17, 25, 38]
4. Institutional fragmentation and policy misalignment in STEM transitions	DBE-DHET disconnect	Weak articulation of bridging/support programs	Fragmented accountability across levels of education	[13, 21, 22]
5. Structural inequalities in STEM access: the urban-rural divide	Infrastructure disparities (labs, ICT, internet)	Unequal distribution of qualified teachers	Aspirational limits shaped by socio-economic context	[3, 9, 26]

Qualitative findings illuminate the mechanisms underlying these trends. They show how curriculum misalignment, subject streaming, uneven teacher development, and weak coordination shape learner trajectories in the STEM-to-engineering pipeline.

This integrated analysis suggests that observed challenges are not isolated or incidental but reflect interconnected systemic dysfunctions within the broader education system. Consequently, strengthening STEM transitions requires coordinated, multi-level interventions that address both structural conditions and lived educational practices.

Beyond its empirical findings, this study contributes theoretically by demonstrating how curriculum misalignment, subject streaming, teacher capacity, and institutional fragmentation function as interconnected mechanisms within a systemic STEM-to-engineering pipeline. Rather than treating these factors as discrete challenges, the study shows how their interaction produces cumulative constraints on learner progression, particularly in unequal education systems [4, 11]. This integrated perspective extends existing STEM pipeline research by foregrounding the relational and systemic nature of educational barriers and aligns with systems-based approaches to education reform that emphasise interdependence across institutional levels [3, 23].

6. Implications of the study

While grounded in the South African context, these findings have broader relevance for education systems characterised by inequality and fragmented institutional structures. Similar patterns of curriculum misalignment, early subject tracking, and uneven resource distribution have been identified in other developing contexts, suggesting that the systemic challenges observed in this study reflect wider global trends in STEM education and workforce development [11, 13].

Framed within the KBE and systems theory, the study highlights urgent systemic reform in South Africa's STEM-to-engineering pipeline to meet 4IR demands. Fragmented curricula, restrictive subject streaming, weak teacher preparation, and structural inequities limit human capital development and innovation potential [4, 14].

Stronger DBE-DHET alignment is needed for coherent curricula and smoother transitions. A national STEM framework with articulation officers, benchmarks, and mapped curricula is recommended [12, 27]. Articulation officers, defined as designated personnel responsible for coordinating curriculum alignment and learner transitions between secondary and post-school institutions, are increasingly recognised as critical to improving STEM pathway coherence [29]. Mathematical Literacy should be reformed or bridged to Pure Mathematics, and equitable resource allocation and ICT infrastructure must address urban-rural disparities [16, 19, 20].

Mandatory, context-sensitive CPD and cross-sector STEM communities are essential. Early career guidance and scaffolded support in post-secondary programs can enhance retention and success in engineering [17, 40].

Longitudinal tracking, disaggregated analyses, and evaluation of CPD and curriculum reforms are critical to generate evidence for equitable, scalable interventions [23, 38].

7. Recommendations

The findings of this study emphasise the need for coordinated, system-level interventions to address persistent leakage in South Africa's STEM-to-engineering pipeline. Convergence between quantitative evidence of learner under-preparedness and qualitative accounts of epistemic discontinuity between secondary and tertiary curricula provides a strong empirical basis for improved vertical curriculum articulation. Misalignment between high school mathematics and science and the cognitive demands of first-year engineering programmes contributes to early academic difficulty and attrition, highlighting the importance of cross-sector curriculum alignment and shared planning across schools, TVET colleges, and universities [6, 36].

Evidence related to subject streaming through Mathematical Literacy further supports the introduction of targeted bridging and alternative access programmes. Qualitative insights from principals, lecturers, and policymakers indicate that many learners with the motivation and potential to succeed in engineering are structurally excluded through curricular tracking decisions. Bridging programmes in mathematics and science, particularly within TVET colleges and universities, are therefore necessary to mitigate exclusion and broaden access to engineering pathways [26, 34].

The study also identifies teacher capacity deficits as a critical mediating factor shaping curriculum enactment and learner preparedness. Survey data and stakeholder narratives underscore the need for sustained professional development focused on advanced subject knowledge, applied STEM pedagogy, and digital competencies [29, 41]. In addition, weak institutional coordination supports recommendations for formalised intersectoral collaboration, including shared data systems and curriculum feedback loops [12]. Collectively, these findings indicate that reducing STEM-to-engineering pipeline leakage requires integrated, empirically grounded reforms aligned with Fourth Industrial Revolution demands [35, 40].

8. Limitations of the study

Several limitations warrant consideration. First, reliance on self-reported data introduces the potential for social desirability bias, particularly among educators and institutional leaders [8]. Second, measures of learner preparedness reflect perceived readiness rather than externally standardised assessments. Third, although the sample includes urban, peri-urban, and rural contexts, provincial representation remains uneven, limiting national generalisability [12]. Finally, technological access constraints in some rural schools may have influenced participation and depth of engagement during data collection, reflecting broader structural inequalities within the education system [26].

9. Conclusion

This study examined the systemic, curricular, and pedagogical factors contributing to South Africa's persistent "leaky pipeline" in STEM education, with particular focus on learner transitions from secondary schooling into tertiary engineering pathways. Framed within the KBE perspective, the findings demonstrate that weak curriculum articulation between secondary mathematics and science and the epistemic demands of post-school engineering programmes undermines learner readiness and contributes to early attrition [12, 14, 36]. The study further shows that subject streaming, especially through Mathematical Literacy, operates as a structural gatekeeping mechanism that restricts access to engineering pathways and disproportionately affects learners from rural and low-income contexts, reinforcing existing educational inequalities [26, 34]. In addition, persistent shortages of qualified STEM teachers, limited pedagogical depth, and uneven exposure to applied and digital competencies constrain effective curriculum enactment, weakening learner preparedness for post-school STEM study [29, 41]. These challenges are exacerbated by weak coordination across the basic and post-school education sectors, resulting in fragmented interventions that fail to address systemic pipeline leakage. Collectively, the findings underscore that South Africa's STEM-to-engineering pipeline challenges are structural rather than isolated, with significant implications for human capital formation, innovation capacity, and equitable participation in the 4IR [13, 35]. Addressing these interconnected barriers through vertical curriculum alignment, targeted teacher professional development, and equitable resourcing is therefore both an educational and socio-economic imperative. By aligning policy, practice, and institutional reform within KBE principles, South Africa can strengthen STEM transitions, reduce persistent attrition, and cultivate a future-ready workforce capable of driving inclusive, knowledge-driven development.

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Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the College of Education, University of South Africa, 2021/05/12/57643482/19/am.

Data availability statement

Data set can be made available upon request at: magadzai@gmail.com

Conflicts of interest

The author does not have competing interest to declare.

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