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A Framework for STEM Competency Alignment

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With the fast evolution of the labour market and global challenges, there is strengthening calls to equip students with STEM competencies that are imperative to navigate the complexities of the future. Yet, several studies have flagged significant disparities between the required STEM competencies and those cultivated within academic institutions, calling for a thorough analysis of contextualised disparities and the formulation of strategic recommendations to mitigate them. Using a mixed-methods design, this case-study addresses this call by foregrounding the perspectives of 438 students, all members of a school-based STEM club, to develop a comprehensive and contextualised 'STEM competency framework' based on the quantitative factor analysis and qualitative thematic analysis. The study also underscores how the developed framework served a dual purpose, as a diagnostic tool for identifying gaps in competency development and as a guide to formulate targeted, evidence-based recommendations. The framework was developed based on loadings of 80 STEM competencies under 16 STEM factors and 4 domains namely the (i) core analytical & problem-solving, (ii) innovation & value creation, (iii) social & collaborative intelligence and (iv) critical inquiry & adaptation. The framework provides a systematic tool for institutions to audit and realign curricula. Its application also guides strategic resource allocation and pedagogical shifts, promoting a more holistic and contextually relevant STEM education that better prepares students for future demands'.

Keywords: STEM (science, technology, engineering and mathematics), competencies, student voice, framework, transformative STEM education

INTRODUCTION

Though the idea of STEM (Science, Technology, Engineering and Mathematics) education emerged in the year 1992 as a response to the declining students' performance in science and mathematics in the United States, it only became a global priority in 2010, generating policies and funding initiatives to develop STEM competencies in learners, improve STEM literacy and encourage integrated learning approaches (Breiner et al., 2012; Bybee, 2013). Today, STEM education is considered as a cornerstone in developing competencies needed to venture the 21st century (Elliott

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et al., 2022) and address world's most pressing challenges such as climate change, public health crises, energy and food security crises among others (Collis, 2019; Atchia, 2022). In response to this imperative, the education systems of most countries have been steering to increase enrolment rate and achievement in STEM subjects, to ensure that learners develop STEM competencies. Yet, analysis of the literature revealed significant disparities.

The first disparity is that even with the increased focus on STEM subjects, the enrolment and performance rates in STEM subjects across various countries, including Scotland (McConnell, 2024), United Kingdom (Smith and White, 2025), Australia (Kennedy et al, 2018) and Mauritius (Maulloo and Naugah, 2017; Rumjaun et al. 2023) are still on the decline. Secondly, there is persistent mismatch between the required STEM competencies to navigate the complexities of the future and those cultivated within specific academic institutions (Janpirom et al., 2025; Abina et al., 2024). In Mauritius, these disparities have been attributed to various factors, including limited career awareness, perceived low job prospects, apprehension as challenging subjects, inappropriate didactics, limited teacher preparedness, use of exam-oriented conventional teaching methods and the lack of a diagnostic assessment mechanism to identify competency mismatch or gap (Rowtho et al., 2025; Ramsurrun et al., 2025; Rumjaun et al., 2023).

Thirdly, while established frameworks from international bodies like UNESCO and the OECD provide valuable macro-level guidance, a critical research gap remains. They often fail to capture the specific contextual realities and student-informed perspectives of individual learning environments. This limitation restricts their usefulness for diagnosing precise, local gaps and for formulating actionable, school-level improvement strategies. To address these gaps, using a case-study approach underpinned by a mixed-research methodology, this study developed and applied a novel, contextualised diagnostic framework. Its primary novelty lies in its grounding in empirical, student-informed data and its structured focus on contextualised actionable STEM competencies and domains. The framework serves a dual purpose, as a diagnostic instrument for identifying specific developmental gaps and as a strategic guide for creating targeted, evidence-based recommendations.

RESEARCH AIM AND OBJECTIVES

Research Aim:

The aim of this study was to diagnose the precise misalignments in STEM competency development within a specific school context and to generate contextualized strategies for improvement.

Research Objectives:

- To develop a student-informed, contextualised, and domain-driven framework for assessing STEM competency development in educational institutions.
- To apply this framework to identify specific competency gaps within a case-study school.
- To formulate actionable, evidence-based recommendations for the institution to mitigate the identified gaps.

LITERATURE REVIEW

To lay the cognitive foundation needed to navigate this study, this section gives an overview of the origin and evolution of STEM education, the importance of STEM education, and the status of STEM education in Mauritius.

Origin and evolution of STEM education

The emergence of the STEM concepts, with siloed emphasis on the individual STEM subjects, dates to 1992 in the joint NASA and the Society of Hispanic Professional Engineers STEM project and in 1998 at the University of Massachusetts, Amherst's STEM Teacher Education Collaborative (STEMTEC) (Vahidy, 2019). STEM, as an educational framework emphasising the interconnections among the different domains, was introduced by the U.S National Science Foundation (NSF) in 2001. Originally termed SMET, the acronym was refined to STEM, by Judith Ramaley, then NSF Assistant Director for Education and Human Resources, or Peter Faletra, Director of Workforce Development at the Department of Energy (Sanders, 2009).

Though the acronym STEM is unanimously accepted to stand for science, technology, engineering and mathematics, the definition and understanding of STEM is much contrasted. For some, STEM is simply the recognition that its four elements have enough in common that they might be of interest to the same group of education specialists, but there is no requirement that they be blended instructionally. From this perspective, STEM education has a compartmentalised dimension where the focus is on any of the four elements (Felder and Brent, 2024). On the other hand, this perspective stands in direct opposition to the recent position statement on STEM education from NSTA (National Science Teaching Association) that explicitly advocates for an integrated STEM (iSTEM) approach. iSTEM education emphasises the interconnectedness of STEM fields, promoting a holistic approach where learning in one area enhances understanding in another. iSTEM encourages the application of competencies - that is knowledge, skills, attitudes and values- across disciplines through real-world problems and projects, fostering deeper learning and innovation (Breiner et al., 2012). This approach aligns with the educational goals of developing learners who are not only knowledgeable but also capable of applying their learning in practical and meaningful ways. The emphasis here is on the development of STEM competencies rather than on knowledge and understandings only.

The importance of STEM education

The rapid transformations evidenced during the last decades, driven by globalisation, technological advancements, demographic shifts and sustainability challenges, have underlined the importance of STEM education in preparing students for an uncertain and dynamic future (OECD, 2017). With automation and artificial intelligence reshaping industries, traditional career pathways becoming obsolete, and the demand for interdisciplinary and adaptable sets of STEM competencies for employability (Schwab, 2016), STEM education is gaining traction around the world, including Mauritius. Hajkowicz et al. (2016) explained that the fourth Industrial Revolution has already started to redefine high-status STEM professions by integrating big data, automation, and virtual reality into core processes (Hajkowicz et al., 2016). Given these

fundamental shifts, education systems must move beyond rigid and structured traditional learning approaches to cultivate problem-solving, adaptability, and digital literacy, which are key competencies that will enable students to thrive in an era of rapid technological evolution (Bakhshi et al., 2017).

STEM education, therefore, plays an important role in developing and nurturing knowledge, skills, attitudes and values needed to transform students into citizens capable of facing current and future challenges. STEM education is important to develop competencies such as inquiry skills, critical thinking, analytical reasoning, technological proficiency, design thinking, collaborative collective, responsibility and open-mindedness, all of which are essential for navigating an increasingly complex global economy (Prinsley & Baranyai, 2015). In fact, recent discourse on 21st-century skills has positioned STEM learning as an essential component of competency-based education, promoting interdisciplinary connections, innovation, and entrepreneurial mindsets (Tytler et al., 2019). Research consistently highlights that STEM education provides a robust platform for cultivating cognitive and non-cognitive skills, including deductive reasoning, technological proficiency, and problem-solving abilities, which are essential for both workforce preparedness and active participation in society (National Science Board, 2015). As the demand for STEM-related expertise continues to rise, education systems must adopt innovative and integrative pedagogies that transcend traditional disciplinary boundaries, ensuring that students are equipped to meet the challenges of the future.

The status of STEM education, focusing on Mauritius as a case-study

Despite the global emphasis on STEM, students' enrolment and performance in STEM subjects remains a persistent challenge across various educational contexts. Several empirical studies (Regan & Dewitt, 2014; European union, 2019) and international assessments such as the 'Trends in Mathematics and Science Study' (TIMSS) and the 'Programme for International Student Assessment' (PISA) have revealed major discrepancies in STEM enrolment, performance and STEM competencies development between advanced, emerging and less developed nations (Kaya & Rice, 2010; Olsen & Lie, 2011). Advanced countries like China, India, and South Korea have seen significant growth in STEM participation, which is often attributed to government policies prioritising science and technology education as a means of economic advancement (OECD, 1997; Jenkins & Nelson, 2005).

In Mauritius, STEM education faces similar challenges as many other countries, despite growing recognition of its importance for national development. Enrolment rates in STEM subjects at the secondary and tertiary levels in Mauritius remain relatively low, partly due to students' perceptions of difficulty and limited career prospects in STEM fields (Lamb & Ball, 1999, Rumjaun et al, 2023). While government initiatives such as the promotion of STEM through school competitions and curriculum enhancements have been introduced, the enrolment in STEM subjects continues to lag other disciplines. Analysis of data obtained from the Mauritius Examination Syndicate (MES), which is the national body responsible for administering and regulating examinations in Mauritius, revealed a declining trend in the performance and number of

students opting for STEM subjects beyond the compulsory level (grade 9) in Mauritius (Rumjaun et al., 2023; Malloo and Naugah, 2017), as shown in Figures 1 and 2.

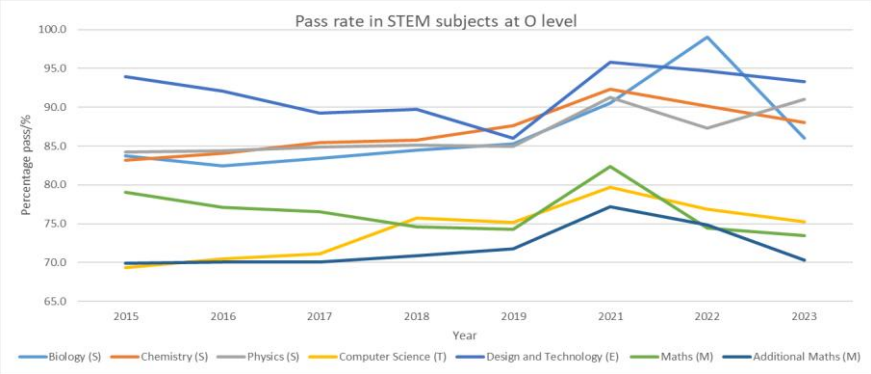

Figure 1
Pass rate in STEM subjects at O level from 2015 to 2023

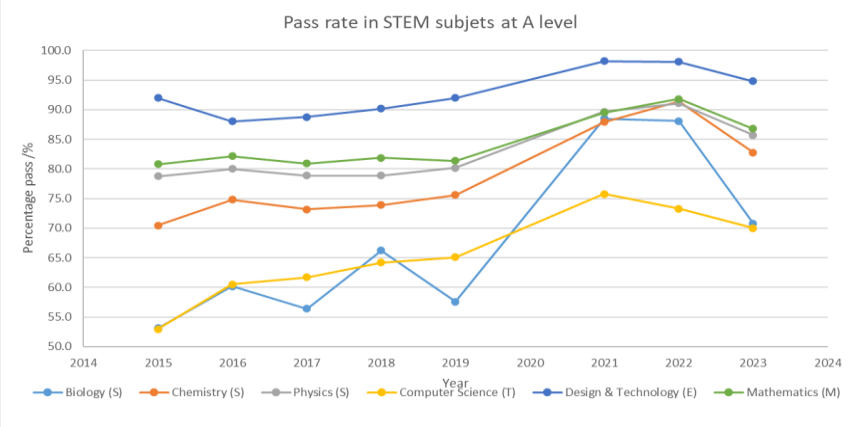

Figure 2
Pass rate in STEM subjects at A level from 2015 to 2023

Research revealed that the causes of the low enrolment and performance of students in the STEM subjects are multifactorial, shaped by a complex interplay of educational, cultural, economic and societal factors (Atherton et al., 2009; Vidal Rodiero, 2007). Researchers have highlighted several factors including students' perceptions that STEM subjects are difficult, abstract, and less engaging as compared to the humanities and social sciences (Cleaves, 2005). The quality of teaching STEM subjects remains a major cause influencing enrolment, as outdated curricula, uninspiring pedagogical approaches, and inadequate teacher training contribute to student disengagement (Bull et al., 2010; Goodrum et al., 2001). Socioeconomic factors further exacerbate disparities, with students from lower-income backgrounds often lacking access to quality STEM education and resources (Davies et al., 2008; Lyons, 2006).

Despite these challenges, Mauritius has made strides in integrating STEM education into its broader educational agenda, aligning with global efforts to enhance scientific literacy and workforce preparedness. Initiatives such as science, mathematics and robotics competitions, coding boot camps, and partnerships with international institutions aim to foster greater interest and participation in STEM disciplines. Moreover, to address these challenges, multifaceted interventions, including curriculum innovation, improved pedagogical strategies, and targeted initiatives are required to promote diversity and inclusion in STEM fields. Rumjaun at al. (2023) and Maulloo and Naugah (2017) explained that the major cause of the low enrolment and performance of students in STEM subjects in Mauritius remain inappropriate pedagogical approaches to teach STEM subjects and to develop STEM competencies. Hurst (2015) and Rumjaun et al. (2024) explained that the STEM teaching model that is currently being used in Mauritius remains compartmentalised instead of integrated, where concepts are developed in a traditional linear and compartmentalised manner, rather than accentuating the connections between the different subjects within STEM, preventing students to develop meaningful understanding and application of concepts. The education system remains mostly knowledge-oriented with limited emphasis on the integrated STEM approach.

The conventional methods of teaching STEM subjects are still characterised by a didactic model, where educators impart knowledge through lectures and textbooks, emphasising rote memorisation and standardized assessments (Martínez-Borreguero, Naranjo-Correa, & Mateos-Núñez, 2022). While these traditional approaches have provided a structured foundation, their limitations have become increasingly evident. Strengths lie in their ability to deliver content efficiently and uniformly across diverse student populations (Banks & Barlex, 2020). However, weaknesses include a lack of emphasis on critical thinking, hands-on application, and real-world problem-solving, which are crucial skills in the world of work. The rigid compartmentalisation of subjects within the STEM disciplines also impedes students' ability to recognise the interconnectedness of concepts (Asghar et al.2012).

Conceptual Framework for Contextualizing STEM Competency Development

Bridging the persistent gap between the STEM competencies cultivated in educational settings and those demanded by the evolving workforce and society requires a diagnostic approach that moves beyond generic frameworks. While macro-level frameworks from organizations like the OECD and UNESCO establish crucial global benchmarks, they often lack the granularity to diagnose specific, contextualized disconnects within individual institutions. This study posits that effective alignment necessitates a tool grounded in the lived experience of the primary stakeholders: the students. Therefore, we propose a conceptual framework centered on a student-informed, diagnostic instrument designed to translate broad competency goals into actionable, institutional-level insights. The framework’s core thesis is that a contextualized gap analysis, structured around empirically derived competency domains, is a prerequisite for formulating effective, evidence-based interventions that enhance workforce readiness, as represented in Figure 3.

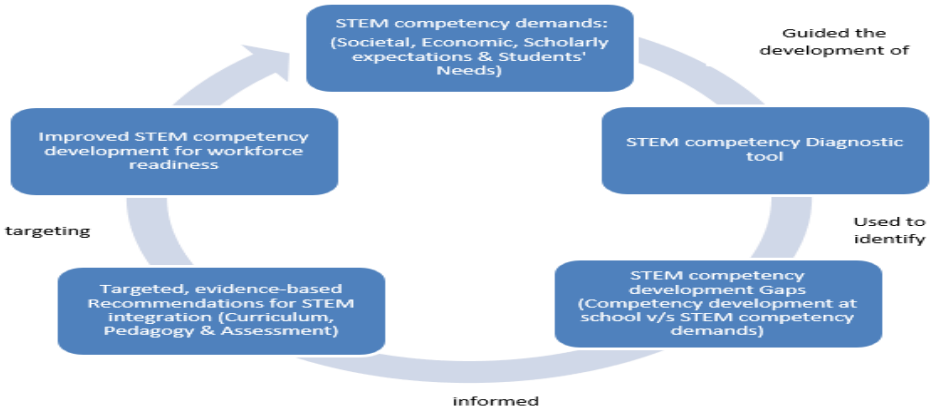

Figure 3
Conceptual Framework

METHOD

This study employs a case-study mixed methodology (Creswell & Plano Clark, 2018), as depicted in Figure 4, to examine students' understandings of STEM education, to identify the STEM competencies that students believe should be cultivated at the classroom level, to develop a 'STEM competency framework' and to validate its use as a diagnostic evaluation tool and a foundation guide to recommend actions to improve competency development.

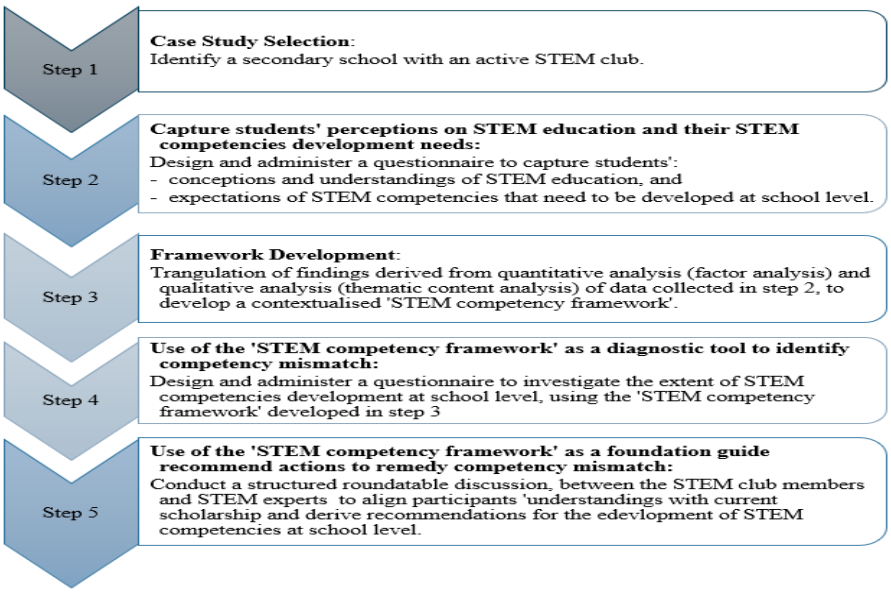

Figure 4
Research design

The selection of the case-study school was done using a purposive sampling procedure, where cases are selected precisely for their capacity to provide rich, contextually relevant insights (Patton, 2015). The selection criteria used to identify the case-study school were (i) a school with an active STEM club, to ensure that participants have at least the basic understandings of STEM education, (ii) have a relatively large number of STEM club members, representing a statistically viable sample size, (iii) a school willing to participate in the research initiative, to provide gatekeeper access, and (iv) a mixed school for gender representations.

Following the selection of a case-study school, a draft questionnaire was developed. After validation by field experts and a pilot study with 15 students, the questionnaire was revised and finalised. It was then administered, upon receipt of signed consent forms, to 438 members of the STEM club to capture their conceptions. and understandings of STEM education, and their expectations of STEM-related skills, attitudes and values that they deem essential to prepare them for the future workforce and support them in addressing current and future challenges (Atchia, 2022; Marginson et al., 2013).These STEM-related skills, attitudes and values, highlighted by the participants, were recorded and analysed, using the quantitative factor analysis and qualitative thematic analysis to identify the STEM competencies, using the development of the 'STEM competency framework'. Factor loadings, using SPSS, was used to identify underlying latent constructs by grouping correlated STEM-related skills, attitudes and values into key competencies (factors) thereby reducing dimensionality, while the thematic content analysis was used to identify the key competencies to be assigned to each grouped correlated STEM-related skills, attitudes and values. Figure 5 below shows the stepwise procedure used in the factor analysis to identify the STEM competencies.

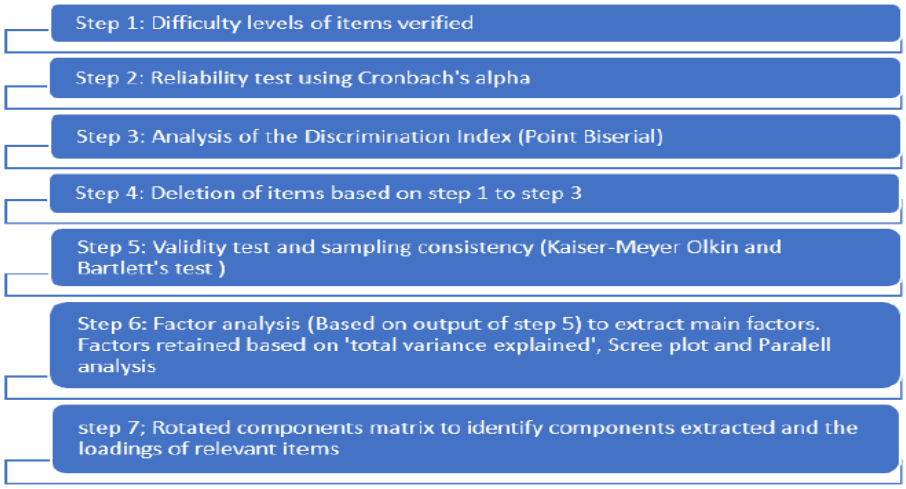

Figure 5
Stepwise procedure used in the factor analysis to identify the STEM competencies (Atchia and Chinapah, 2023)

Following the development of the 'STEM competency framework', a second questionnaire was developed and administered with the participants to assess the extent to which the key STEM competencies (depicted in framework) were currently being developed in schools. Aligned to the case study methodology, this was done to identify gaps in competency development at the selected case-study school (Field, 2022), validating the use of the 'STEM competency framework' as a diagnostic tool to identify contextualised STEM competencies need development.

As the final step, a structured roundtable discussion, between the STEM club members and STEM experts was organised to (i) align participants' understandings with current scholarship, (ii) present the 'STEM competency framework' and the findings of its use as a diagnostic evaluation tool and (iii) develop recommendations for effective STEM competencies development at school level.

FINDINGS

This section presents the findings in the same sequence as depicted in Figure 3.

Step 1: Case Study Selection

The selection of the case-study school was straightforward, as out of all the secondary schools in the country having an active STEM club, only one school had a mixed student population and statistically viable sample size. The selected case-study school had 428 members of the STEM club. The selected STEM club constituted an optimal sample for this study, as it represents the school's most engaged sought-after extracurricular club, ensuring a participant pool with demonstrated interest and investment towards STEM, which is a critical factor for examining pedagogical efficacy and student expectations (Davis et al., 2023). Moreover, the club's structured activities further validate its suitability, as members possess firsthand experience with both formal curricula and applied STEM learning.

Step 2 and 3: Identification of STEM competencies and development of 'STEM competency framework'.

Analysis of the data collected through the google form questionnaire, administered with the 428 members of the STEM club, revealed that all the participants were aware of the letter representations of the acronym STEM as Science, Technology, Engineering and Mathematics. However, most (62%) participants showcased a discipline-specific understanding of STEM education, disconnected from real-world applications. For instance, one of the participants stated the following:

"STEM education puts greater emphasis on the four STEM subjects due to their importance in future careers"

It was also noted that out of the few (38 %) participants displaying understanding of integrating the different STEM disciplines in interdisciplinary learning, only 12% highlighted the variations and extension of integrated STEM to accommodate other disciplines, such as STEAM (Science, Technology, Engineering, Arts and Mathematics), supporting the findings of researchers such as Rumjaun et al. (2024), Hoachlander & Yanofsky (2011) and Li et al. (2023) among others. These limited understandings advocate the need of aligning the participants' understanding of STEM

education and STEM competencies development with contemporary scholarship on STEM education, supporting the initiative of the roundtable discussion (step 5).

In addition to capturing participants' conceptions and understandings of STEM education, the questionnaire also captured participants' expectations of the STEM competencies they believe should be cultivated at the classroom level during STEM subjects' instruction, to prepare them for the future workforce and to address emerging challenges. The data collected from these items were used for both quantitative analysis (factor analysis) and qualitative thematic content analysis, to identify the categorised grouped STEM competencies. Figure 5 presents the findings of the factor analysis and Table 1 summarises the (i) the STEM-related skills, attitudes and values highlighted by the participants as necessary for development at school level and (ii) the key STEM competencies (factors) that emerged from the thematic analysis. In fact, each group of STEM-related skills, attitudes and values that were loaded under a factor was assigned a STEM competency, termed on the basis of the thematic content analysis. Figure 6 shows the 'STEM competency framework'.

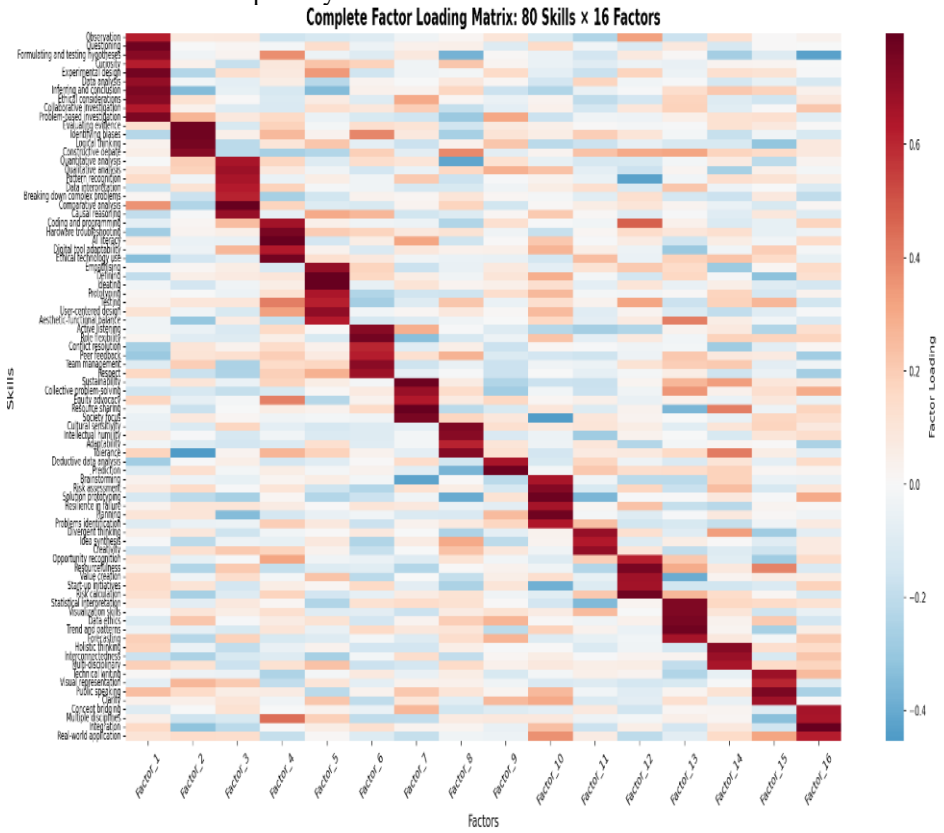

Figure 6
Results of factor analysis

As far as the recommendations to run the factor analysis is concerned, all were tested and found to be in accordance. The Kaiser-Meyer Olkin (KMO) and Bartlett's test chi-square were 0.875 and 38314.9 (Bartlett's test of Sphericity, p-value 0.000), indicating that the data were appropriate for factor analysis. Moreover, based on eigenvalues greater than 1 and the scree plot, 16 components/factors were extracted (figure 6) in line the factor loadings procedures described by O'connor (2000), and Cota et al. (1993). Table 1 shows the results of the thematic content analysis, which was carried out to assign key STEM competencies to the 16 factors loaded during the factor analysis.

Table 1
STEM competencies emerged during factor loadings and thematic analysis

STEM- related skills, attitudes and values (highlighted by participants as crucial for development in schools)	STEM competencies (Themes emerged)
Observation, questioning, formulating and testing hypotheses, curiosity, experimental design, data analysis, inferring and conclusion, ethical considerations, collaborative investigation, problem-based investigation	Inquiry Skills
Evaluating evidence, identifying biases, logical thinking, constructive debate	Critical Thinking
Data analysis, quantitative analysis, qualitative analysis, pattern recognition, data interpretation, breaking down complex problems, comparative analysis, causal reasoning	Analytical Reasoning
Coding and programming, hardware troubleshooting, AI literacy, digital tool adaptability, ethical technology use	Technological Proficiency
Empathising, defining, ideating, prototyping, testing, user-centred design, aesthetic-functional balance	Design Thinking
Active listening, role flexibility, conflict resolution, peer feedback, team management, respect	Collaboration
Sustainability, collective problem-solving, equity advocacy, resource sharing, society focus	Collective Responsibility
Cultural sensitivity, intellectual humility, adaptability, tolerance	Open-Mindedness
Deductive data analysis, logical thinking, prediction,	Deductive Reasoning
Brainstorming, risk assessment, solution prototyping, resilience in failure, planning, problems identification	Problem-Solving
Divergent thinking, idea synthesis, creativity	Innovation
Opportunity recognition, resourcefulness, value creation, start-up initiatives, risk calculation	Entrepreneurial Mindset
Statistical interpretation, visualization skills, data ethics, trend and patterns, forecasting	Data Literacy
Holistic thinking, interconnectedness, multi-disciplinary	Systems Thinking
Technical writing, visual representation, public speaking, active listening, clarity	Communication Skills
Concept bridging, multiple disciplines, integration, real-world application	Interdisciplinary thinking

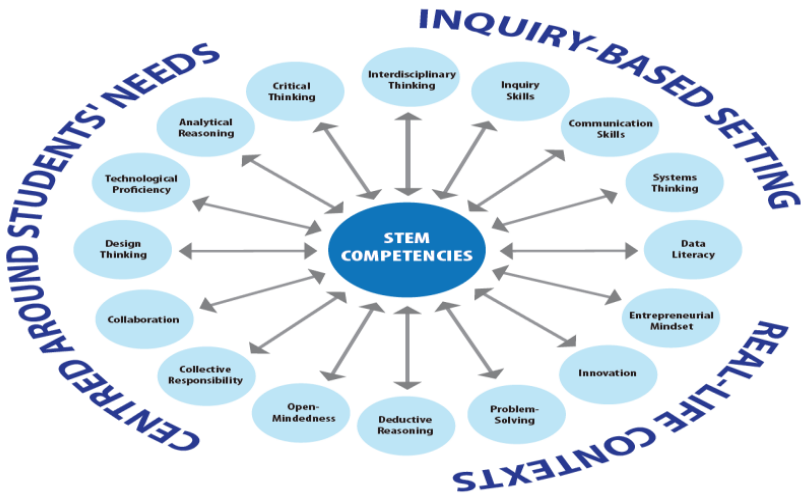

Figure 7
STEM competencies framework

The 'STEM competencies framework' articulates a comprehensive set of core STEM competencies that emerged from students' voices on their competency developmental needs. At its core lies a central nexus of STEM competencies, each interconnected by bidirectional arrows to emphasise the interdependence and dynamic interplay between the key competencies. These competencies are not isolated. The directional arrows show that the competencies are interconnected, and they evolve in connection with others. Encompassing this central cluster of STEM competencies, the framework lays emphasis on three contextual anchors, namely the inquiry-based setting, the real-life context and centeredness around students' needs, which provide the ecosystem within which these competencies are to be cultivated. The three contextual anchors were strongly highlighted by most participants as crucial criteria within which STEM competencies are to be developed. This multi-dimensional structure underscores the notion that effective STEM education is both competency-integrated and contextually grounded.

Step 4: Validation of the 'STEM competencies framework' as a diagnostic tool

To validate the use of the 'STEM competency framework' (figure 7) as a diagnostic tool, it was used as an underpinning frame to design and prepare a quantitative questionnaire. The latter was used as a diagnostic tool to investigate the extent of STEM competencies development at classroom level. The questionnaire comprised sixteen items representing the sixteen categorised STEM competencies identified in step 2, namely inquiry skills, critical thinking, analytical reasoning, technological proficiency, design thinking, collaboration, collective responsibility, open-mindedness, deductive reasoning, problem-solving, innovation, entrepreneurial mindset, data literacy, systems thinking, communication skills and interdisciplinary thinking. Each item utilised a 5-point Likert scale anchored from "never developed" to "extensively developed,"

following established psychometric principles for measuring developmental continua (Boone & Boone, 2012). This scaling approach allowed for nuanced measurement of competency development while maintaining interval-level properties for statistical analysis (Norman, 2010). The average score across all items provided a composite measure of overall competency development, while individual item analysis permits examination of specific competency domains. Figure 8, representing the voices of the STEM club members, shows the extent of STEM competencies development at classroom level.

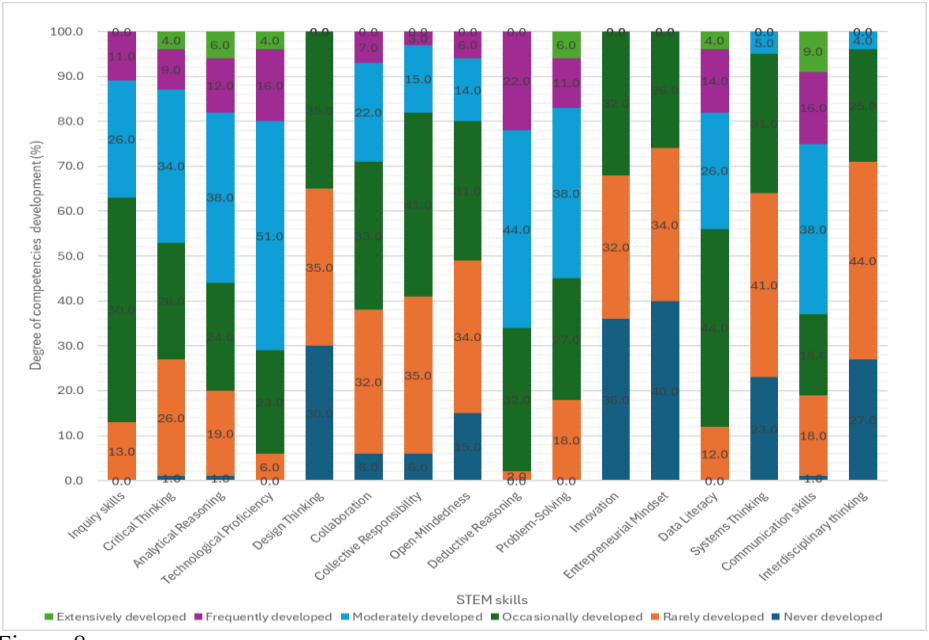

Figure 8
Degree of STEM competencies development at classroom level

Figure 8 provides a quantitative assessment of the development levels of the sixteen critical STEM competencies. Analysis of the data revealed that the highly developed competencies are the inquiry, critical thinking, technological proficiency and problem-solving competencies, positioned at the highest development tier (extensively/frequently developed), reflecting their well-established emphasis in the school curricula. In fact, both the lower secondary National Curriculum Framework (NCF, 2017) and the upper secondary Cambridge syllabi ('O' and 'A' level levels) lay much emphasis on these competencies, which are major assessment criteria of the syllabi of STEM subjects. Skills falling under inquiry, critical thinking, and problem-solving competencies such as observation, questioning, formulating and testing hypotheses, curiosity, experimental design, data analysis, inferring and conclusion, collaborative investigation, problem-based investigation, evaluating evidence, identifying biases, logical thinking, coding and programming, hardware troubleshooting, and digital tool adaptability are extensively developed at classroom

level during practical classes. The moderately developed competencies, such as the analytical reasoning and communication skills, which fall under the mid developmental tier (moderately/occasionally developed) indicate gaps in analysis and communications. The underdeveloped competencies, such as entrepreneurial mindset, deductive reasoning, design thinking, interdisciplinary thinking and innovations, appear in the lowest tiers (rarely/never developed), which is often attributed to curricular overemphasis on traditional skills over emerging needs. indicating inconsistent integration despite workforce demands.

To facilitate the subsequent formulation of recommendations for bridging the identified STEM competency gaps (step 5), which represents the misalignment between industry requirements and the competencies developed in the specific school context, a second factor analysis was conducted. This analysis aimed to reduce the skill set into its principal latent constructs, thereby identifying critical leverage points for intervention. Figures 9 (skills correlation heatmap) and 9 hierarchical clustering dendrogram) show the top correlations (highest co-movement pairs) depicted during factor loadings analyisis, which led to the emergence of four main clusters namely cluster 1 (core analytical and problem solving), cluster 2 (innovation and value creation), cluster 3 (social and collaborative intelligence) and cluster 4 (critical inquiry and adaptation), as described in Table 2.

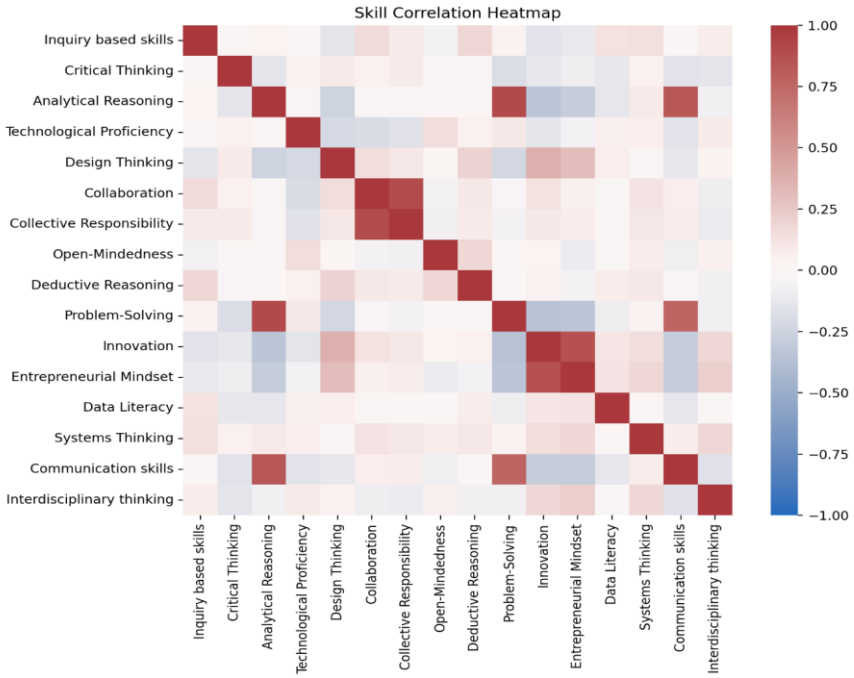

Figure 9
Skills correlation heatmap

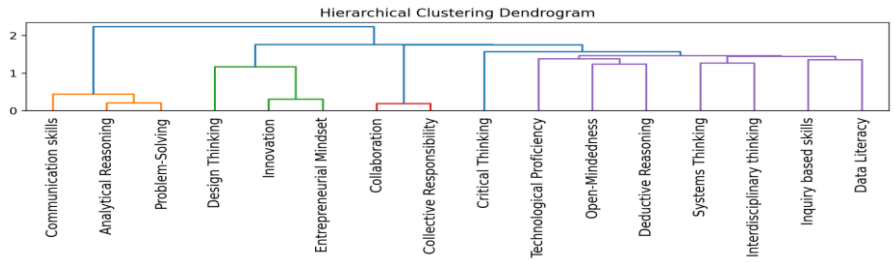

Figure 10
Hierarchical clustering dendrogram

The factor analysis successfully reduced the 16 specific skills into four broader, more fundamental competency domains, which guided the discussions and development of recommendations (step 5) that aim at bridging the competency gaps.

Table 2
Competency domains

Category	Skills Included	Description of the Latent Factor
Core Analytical & Problem-Solving	Analytical Reasoning, Deductive Reasoning, Problem-Solving, Systems Thinking	The cognitive ability to deconstruct problems, apply logic, and develop structured solutions.
Innovation & Value Creation	Design Thinking, Innovation, Entrepreneurial Mindset, Interdisciplinary Thinking	The capacity to generate novel ideas, create value, and synthesize knowledge across domains.
Social & Collaborative Intelligence	Collaboration, Collective Responsibility, Open-Mindedness, Communication Skills	The interpersonal skills required to work effectively in teams toward common goals.
Critical Inquiry & Adaptation	Inquiry Skills, Critical Thinking, Data Literacy, Technological Proficiency	The capability to acquire, critically evaluate, and utilize information and technology effectively.

Step 5: Roundtable Discussion

The roundtable discussion was conducted at the seat of the school to engage the members of the STEM clubs with carefully selected international and national professionals and experts in STEM fields. This was done to respond to participants' queries and align their understandings, before proceeding with the capture of students' recommendations on how these competencies may be developed in the specific context of their school.

The first part of the roundtable discussion, conducted in a hybrid mode where two out of the five experts intervened online, successfully aligned the students' understandings of STEM education with the contemporary scholarship and most recent research orientations of the future of STEM education. Centered around the origin, evolution and future of STEM education, with a special focus on STEM competencies development, it was noted that the students were fully engaged in a dynamic exchange with the experts, revealing both convergent and divergent views on critical aspects of STEM learning. Analysis of the discourse indicated a shared recognition of the evolving nature of STEM disciplines and their implications for pedagogical approaches, in addition to the understanding of the key STEM competencies and their importances.

The second part of the session, which included the presentation of STEM competencies domains, the 'STEM competencies framework' and the findings derived from its use as a diagnostic tool, led to the emergence of the following recommendations to improve STEM competencies' development in schools:

- To develop and engage students in co-curricular and extra-curricular STEM-based projects. Then organise open days to exhibit students' work.
- To engage students in whole-school projects, where Community of Practice that include representatives of all stakeholders are set in view of identifying and addressing issues found within schools using the STEM approach.
- Organise school-wide activity weeks on selected STEM-related themes.
- Provide career guidance support to students interested in STEM careers.
- Replace isolated disciplinary activities by interdisciplinary projects.
- Train teachers to implement STEM pedagogies effectively.
- Develop structured professional development workshops for teachers and students, on STEM education with emphasis on development of STEM competencies.
- Create innovation hubs with tools (e.g 3D printers, coding kits) in school library and labs, for students to prototype solutions to local problems (e.g., water scarcity and high electricity consumption).
- Create opportunities to partner with local industries, NGOs and national/international experts (such as engineers) to co-design classroom or school projects.
- Organise talks, field visits, webinars and mentoring sessions with STEM professionals.
- Use role-playing, such as the mock parliament that was organised by MGI schools, to develop systems thinking, collective responsibility and communication competencies among students.
- Empower students to set school clubs such as the STEM club, coding club and data literacy club, that advocate for STEM priorities.
- In addition to examination, assess students' competencies development. Marks for internal examinations may be allocated for students' engagement in co- and extra-curricular activities. For instance, students may be asked to develop a digital portfolio that document their co- and extra-curricular activities emphasising on STEM competencies development.
- Facilitate the organisation of public exhibitions where students present projects to families and experts, practicing communication skills and receiving feedback.
- Encourage the use AI tools, such as ChatGPT for brainstorming and TinkerCAD for design, while taking into consideration the ethical dimensions of its use.
- Promote interdisciplinary thinking and innovations in curricular, co-curricular and extra-curricular activities, as global issues such a climate change, energy crisis, water crisis are all interconnected.
- Rewards students for progress in STEM competencies development during Prize giving ceremonies.
- Host guest speakers from non-traditional STEM fields (e.g., artists using AI, social entrepreneurs) to broaden perspectives on open-mindedness.

- Develop or host school-wide or inter-school innovation days, hackathons, or design thinking boot camps to encourage creativity and solution-oriented thinking.
- Encourage, motivate and support students to take part in science fairs, innovation expos, robotics challenges, and entrepreneurship contests at national and international levels.
- Engage in exchange programmes with regional and international schools on STEM-related themes
- Engage schools with industry through expert talks, internships, mentoring programmes, or short-term student placements to expose students to real-world challenges and foster an entrepreneurial mindset.
- Engage students in start-up competitions.
- Provide students with spaces and resources to explore entrepreneurial ideas and prototype products.
- Train both teachers and students in the design thinking process to encourage creative problem-solving and user-centred innovation.

DISCUSSION

With the rapidly evolving technologies such as AI and big data technologies, globalisation, economic unpredictability and complex societal challenges, the industry's demands on the education system have evolved. According to Wang and Juslin (2012), WEF (2020) and Elisha (2024), today's education systems should equip students with STEM competencies that goes beyond traditional knowledge and skills development, to cultivate a robust and future-ready workforce that respond to the evolving industry demands. Yet, the WEF (2020) has flagged significant disparities between industry-required STEM competencies and those cultivated within academic institutions, advocating for a systematic evaluation of the current education system and individual academic institutions under the lens of STEM competencies frameworks, such as the UNESCO framework for STEM competencies (Soo Boon, 2019) or more contextualised frameworks, such as Hu and Guo (2021) conceptual framework for STEM curriculum design. Several researchers in the field, including Zhou et al. (2022), Crompton (2020) and Cumming (2010) highlighted the need to develop country-specific and institution-specific contextualised frameworks that stemmed from students' needs and respond to industry's requirements. Thus, supporting this study in developing a contextualised framework (Figure 7), that is used both as a diagnostic tool and as a guide for the development of contextualised and responsive actions that promote development of STEM competencies amongst students.

The framework not only identifies 16 key competencies from students' voices, namely inquiry skills, critical thinking, analytical reasoning, technological proficiency, design thinking, collaboration, collective responsibility, open-mindedness, deductive reasoning, problem-solving, innovation, entrepreneurial mindset, data literacy, systems thinking and communication skills, interdisciplinary thinking, but also functions as a diagnostic tool, revealing disparities in their development. Figure 11 is a Wordcloud, derived from data collected through the use of the framework as a diagnostic tool.

Figure 11
Wordcloud on STEM competencies development

The wordcloud represents the extent that the sixteen contextualised critical STEM competencies are currently developed at school level. The font size used is directly proportional to the extent that each STEM competency is currently developed at classroom or school levels. According to several researchers, including Fan et al. (2021) and Mohan (2023), such baseline data has dual functions, enabling educators and other stakeholders within schools to identify the gaps in STEM competency development and guide them in developing targeted recommendations and interventions. It was noted that the STEM competencies framework (figure 7) and the identification of the STEM competencies domains (Table 2) offered a robust mechanism for evaluating students' skill sets in an authentic and meaningful way. These enabled educators to identify strengths and gaps in students' STEM capabilities and to create bidirectional links between skills signal and deficiencies. For example, weak analytical reasoning was correlated with the lack of problem-solving and system thinking skills. Such analyses informed the participants and guided them in developing recommendations that aimed at enhancing STEM competencies development.

In fact, the framework served as a guide for the development of contextualised and responsive pedagogical actions. By pinpointing specific areas of need within a student's skill profile, educators can design targeted interventions and learning experiences that promote growth in those competencies. For instance, recommendations made for limited innovation or entrepreneurial mindset was to introduce project-based learning scenarios that simulate real-world challenges requiring creative and enterprising solutions. The student-centred dimension of the framework further ensures that these interventions are tailored to learners' interests and experiences, thereby enhancing engagement and efficacy. Ultimately, the framework not only supports skill development but also fosters a reflective and adaptive educational ecosystem responsive to the evolving demands of STEM education.

In addition to the potential of using such contextualised framework as a diagnostic tool to identify competency mismatch and guide meaningful actions, this framework has the added value of being grounded in students' voices. In fact, by foregrounding students' voices in framework development, it ensures that the framework is stranded in the lived realities, aspirations, and contextual needs of its primary beneficiaries, that is students

themselves. Traditional frameworks, such as those developed by the UNESCO (2019), OECD (2018) or the National Research Council (2012), while comprehensive, are often expert-driven and may not adequately reflect the nuanced perspectives of learners, particularly in diverse socio-economic and cultural contexts. By contrast, the student-informed framework enables a bottom-up approach that captures emerging youth priorities, which are frequently underemphasised in top-down models. Recent scholarship underscores the importance of students' agency in curriculum development and competency framing (Cook-Sather, 2020; Mitra, 2018) and pedagogy (Robinson and Taylor, 2007), arguing that meaningful inclusion of student perspectives leads to more equitable and relevant educational outcomes. In fact, Mitra (2018), Fielding (2011) and Moss (2020) stated that students, if made agentic in their learning environment, become critical, creative, socially responsible and active decisions makers.

The contextualized framework, which represents a critical advancement over established macro-level models promulgated by global organizations such as UNESCO, the OECD, and WEF, is operationalised through several key mechanisms. Primarily, it bridges the persistent policy-practice gap. Global frameworks effectively highlight what competencies are required but offer limited depth regarding how these competencies can be pedagogically nurtured within specific socio-cultural and institutional contexts (Marginson et al., 2013). By centering student voices, the contextualized framework translates abstract global goals into actionable, localised strategies. It identifies the authentic enablers and barriers to engagement as experienced by learners, ensuring interventions are responsive to on-the-ground realities rather than being merely aspirational impositions from above (Archer et al., 2020).

Furthermore, the contextualised framework expands the dominant human capital paradigm of future readiness. While macro-level models often prioritise STEM for economic competitiveness and workforce development (OECD, 2018), a student-informed framework provides a more holistic and critical vision of citizenship. This perspective aligns with the humanistic vision but crucially deepens it by grounding abstract principles in the emergent values of the rising generation. **CONCLUSION**

This study underscores the indispensable role of student voices in shaping a future-ready education system, particularly in the context of STEM learning and STEM competencies development. The STEM competencies framework, developed in this study not only emphasised the key competencies that students prioritise for workforce readiness and societal engagement, but also functioned as a diagnostic tool to expose critical gaps often overlooked by existing, top-down models. However, we acknowledge that the framework is not a pedagogical prescription and its potential to enable a shift beyond one-size-fits-all approaches is contingent upon its integration with supportive pedagogical models, professional development for educators, and systemic changes in teaching design. Used in this way, the framework can provide a foundational reference for developing more targeted and responsive strategies, ultimately guiding efforts to prepare students for future workforce and societal challenges.

This study is not without its limitations. Principally, the framework's development within a single-case context necessitates caution regarding broad generalisability.

Consequently, we propose that a vital direction for future research involves rigorous, cross-country validation to assess the transferability and robustness of these student-prioritised competencies. Extending this work through comparative international studies would powerfully demonstrate its capacity to advance equitable STEM development worldwide.

AUTHOR CONTRIBUTIONS

This study was conceived and designed by Dr. Shakeel Atchia. Data collection and preliminary analysis were carried out by Zakiyyah Atchia, the founder and current president of the School's STEM club. Though interpretation of results and drafting the manuscript were done by both authors, it was led by Dr Shakeel Atchia with view of building capacity of the second author. Both authors reviewed, edited, and approved the final version of the manuscript.

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