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Structural Barriers and the 4Cs Crisis: How Infrastructure Challenges Undermine Critical Thinking, Collaboration, Communication, and Creativity in Global STEM Higher Education

Zafar Iqbal*

Faculty of Education & Social Sciences, SZABIST University Islamabad Pakistan

*Corresponding author: zfr.shah3@gmail.com

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ABSTRACT

The 4Cs critical thinking, collaboration, communication, and creativity are widely recognized as core competencies for STEM graduates, yet their systematic development within undergraduate programs across higher education institutions remains insufficiently examined, particularly in lower-middle-income contexts such as Pakistan. Notably, while infrastructure is widely acknowledged as a prerequisite for quality education, there is scant empirical, student-centered evidence on how structural infrastructure barriers specifically constrain the development of all four 4Cs competencies in STEM higher education settings. Objectives of the study were to examine how inadequate lab equipment, physical space constraints, and timetable conflicts constrain critical thinking and collaborative learning among STEM students in higher education institutions. To investigate how insufficient presentation technology, limited writing support, absent maker spaces, and rigid assessment methods impede scientific communication and suppress creative thinking in STEM higher education. A qualitative research design was applied; twenty semi-structured interviews were conducted with undergraduate STEM students across higher education institutions in Pakistan to explore lived experiences of infrastructure constraint. Findings reveal a persistent gap between nominal resource provision and functional adequacy. Critical thinking is suppressed by outdated laboratory equipment and procedurally rigid instructional methods. Collaborative learning is constrained by limited physical spaces, inflexible timetable, and discipline-inadequate digital tools. Communication development is undermined by unreliable presentation technology and insufficient scientific writing support. Creativity emerges as the most infrastructure-dependent competency, with restricted access to maker spaces, prototyping facilities, and flexible assessment frameworks collectively inhibiting experimental engagement. Our findings contribute empirical, student-centered qualitative evidence from an underrepresented Pakistani STEM higher education context and affirm patterns of educational underinvestment consistent with broader lower-middle-income contexts. This study urges institutions and policymakers to priorities targeted infrastructure investment and integrate infrastructure standards within STEM accreditation frameworks to ensure equitable 4Cs development globally.

◆ **KEYWORDS:** STEM higher education; 21st-century skills; Critical thinking; Collaboration; Communication; Creativity; Educational infrastructure; Structural barriers.

1. INTRODUCTION

Today, with the world's economy becoming more complex and technology changing at a faster pace, higher education institutions are under constant pressure to look beyond the skills of the individual disciplines and focus on developing the competencies of their students. In the era of the 21st century skills, the notion of the four core competencies (4Cs) namely, critical thinking, collaboration, communication, and creativity has become a key organizing principle for education reforms across the globe (Thornhill-Miller et al., 2023; Guerra, 2024). These competencies are especially important in the science, technology, engineering and mathematics (STEM) disciplines, where STEM is considered to be the main source of innovation, economic productivity and solutions to global challenges. (Birru, 2024; Aslam et al., 2023). There has been a lot of research on the positive impacts of STEM education on higher-order thinking and problem-solving skills in students (Lin et al., 2023; Zhang & Ma, 2023). Many studies have demonstrated that 4Cs (Content, Critical thinking, Communication, and Computing) can be effectively encouraged in quality learning environments for STEM subjects, which include well-equipped laboratory spaces, collaborative learning areas, and spaces for technology-based learning (Kwon & Lee, 2025; Nagesh et al., 2024). But the circumstances needed to make this transformative potential happen are not fairly shared across global higher education systems. Poor facilities, outdated equipment and unstable digital connections, as well as

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poorly trained teaching personnel are systematic structural obstacles that dampen the capacities these institutions seek to support and are commonly known as infrastructure shortcomings. (Thompson & Williams, 2024; Sarong & Adelekan, 2024). Educational infrastructure is much more than the buildings and equipment. In the field, scholars have at least four dimensions related to the infrastructure for education that could be connected: (i) Physical Infrastructure (laboratories, classrooms, and learning spaces), (ii)Digital Infrastructure (internet access, hardware, and educational technologies) (iii) Human Infrastructure (faculty qualifications, pedagogical training, and academic support services) (iv) Institutional Infrastructure (policy frameworks, funding mechanisms, and governance structures (Sarong & Adelekan, 2024; Pierce & Cleary, 2024). Students' pedagogical spaces to question assumptions, evaluate evidence, and express logical arguments require to be developed for critical thinking as it has been studied most broadly amongst the 4Cs (Aston, 2024; Guerra, 2024). Four communication skills, including oral, written, and multimodal scientific expression, need institutional investment to build presentation facilities, academic writing assistance, and language development programs, which are often lacking in under resourced institutions (Birru, 2024; Goldberg et al., 2023). Specifically, creativity in STEM, which refers to the ability to think creatively, design innovatively, and problem solve imaginatively, is especially at risk when the curriculum is highly standardized and focused on assessment, and when there are fewer makerspaces, innovation laboratories, and project-based learning opportunities (Kwon & Lee, 2025; Nagesh et al., 2024). Therefore, it is not enough to simply reform the curriculum, all four dimensions of the 4Cs require real investment in the structural circumstances of learning (Assefa et al., 2025; Aslam et al., 2023).

Problem statement

Although the 4Cs (critical thinking, collaboration, communication, and creativity) have been agreed upon as key learning outcomes for a STEM higher education experience, many institutions continue to experience ongoing infrastructure challenges that impede their progress. The effects of physical, digital, human, and institutional infrastructure on student acquisition of these skills, however, are not well understood, and this presents a significant gap in the literature. The absence of evidence will limit the capacity of universities and policymakers to create evidence-based and targeted interventions to enhance 21st century skill development in STEM education

Objectives of the study are:

I. To examine how inadequate lab equipment, physical space constraints, and timetable conflicts constrain critical thinking and collaborative learning among STEM students in higher education institutions.
II. To investigate how insufficient presentation technology, limited writing support, absent maker spaces, and rigid assessment methods impede scientific communication and suppress creative thinking in STEM higher education.

Significance of the Study

This study thus contributes meaningfully to both local policy reform and the broader international discourse on equitable 4Cs development in STEM higher education.

Review of Literature

As part of the global knowledge economy of the twenty-first century, four related skills critical thinking, collaboration, communication, and creativity have become the focus of higher education policy and practice (Romero, 2026; Ananiadou & Claro, 2009). The 4Cs framework was formally stated by the Partnership for 21st Century Skills, which holds that these skills are essential for success in the workplace, for civic engagement, and for living in an increasingly complex world (Trilling & Fadel, 2009; Griffin et al., 2012) In STEM, the 4Cs of learning (critical thinking, communication, collaboration, and creativity) are also learning outcomes and pedagogical processes. Therefore, STEM education is not just about learning content but also developing the skills necessary for success in the 21st century (Vithanage & Nakashima, 2025; Caratozzolo et al., 2024). This rhetorical uniformity blurs the differences between institutional stances and the actual practices of education, and a gap has been left which has not yet been sufficiently theorized or explored empirically. Infrastructure deficits - physical learning environments, digital connectivity, laboratory resources, institutional funding, and others - have become primary, but frequently overlooked, ways in which the 4Cs are systematically being undermined in STEM higher education worldwide. (Sarpong et al., 2025; Jamaluddin et al., 2025).Geographic inequalities especially in sub-Saharan Africa, South Asia, and parts of Latin America, still face extreme resource constraints while high-income countries have made significant investments, although not comprehensive, for infrastructure in STEM learning education (World Bank, 2024; Sarpong et al., 2025).

Conceptual Foundations for 4Cs Development:

In terms of the theories, the relation between learning and educational infrastructure is based on constructivist and socio-material theories that suggest that the learning environment has an impact on the development of cognition and collaboration (Vygotsky, 1978; Bronfenbrenner, 1979). This perspective is one that supports the 21st-century skills framework, seeing physical and digital infrastructure as what is needed to develop the 4Cs. Pedagogy, assessment, and learning environments all need to be aligned to facilitate effective cultivation of these competencies. The 4 Cs are interdependent, and therefore, if one of these is missing, the other three can be as well, leaving students with a wider learning gap (Griffin et al., 2012; Vogt & Roblin, 2012).

There is more and more literature which has differentiated between first, second and third order infrastructure barriers. First order barriers are related to physical access, as whether there is equipment, space and connectivity. Second order barriers are

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associated with quality and reliability. Third order barriers are pedagogical and institutional norms that hinder the use of even available infrastructure to the greatest extent (Lee et al., 2019). Importantly, this taxonomy shows that there are not only material infrastructure problems, but they are also institutional.

Physical Environment, Classroom Design, and the 4Cs:

Physical learning environment is often overlooked and one of the most basic dimensions of STEM higher education infrastructure. Pedagogical science and environmental psychology findings converge to confirm the pedagogical non neutrality of the spatial organization of learning environments. Overcrowding is one of the most widespread physical constraints in global higher education in science, technology, engineering and mathematics (STEM) in the rapidly growing higher education systems of the Global South. In Pakistan, Rahim et al. (2025) found that classrooms were too crowded, leading to higher stress levels, limited participation and lower academic confidence among university students, all of which were directly proportional to good classroom conditions needed for collaborative learning and creative risk-taking. In a systematic review, Vakili et al. (2024) found that a lack of space in college classrooms led to less individualized attention, less collaborative learning, and the difficulty of effective classroom management. According to ED spaces (2025), the STEM spaces with collaboration areas, movable furniture and technology stations built into the space are correlated with increased engagement, but these spaces are not found in most institutions, particularly in the lower resource tier. (Cooper et al., 2025).

Digital Infrastructure, Connectivity, and 4Cs Suppression:

Digital infrastructure internet access, devices, software, and technical support is a critical determinant of 4Cs development in STEM higher education. The COVID-19 pandemic exposed pre-existing digital divides, with millions of STEM students losing access to simulations, collaborative tools, and scientific databases overnight. Over 2.5 billion people globally remain offline, disproportionately affecting STEM students across the Global South (ITU, 2025). Inadequate digital infrastructure, outdated ICT policies, and unprepared faculty collectively impede 21st-century skill development in STEM programs. Students attending school via their mobile devices in low-income settings are hindered by structural barriers to access of simulation platforms and research databases needed for critical thinking (Zhang & Livingstone, 2024). AI-enabled tools have the potential to positively affect all four 4Cs, but can also exacerbate skill gaps if there is an infrastructure disparity (Chen et al. 2025). These attributes of communication, creativity and critical thinking are directly curtailed by digital deficits in Pakistan universities. (Rahman et al., 2025; Sarong et al., 2025).

Laboratory Resources, Equipment, and the Suppression of Creativity:

Based on the results of the meta-analysis, when project-based learning is properly resourced, the effect is significant, but when it lacks sufficient infrastructure, limited autonomy, or limited time, the effect is not significant (Kwon & Lee, 2025; Garcia-Morales et al., 2026). This is especially true in the Global South, where only half of STEM and computer labs are operating in universities, as reported by Brookings (2023), which directly hinders hands-on creative problem-solving. These trends are observed in Ghana, where Physics departments have no basic research equipment (Sarong et al., 2025), and where ICT departments have been teaching their students computer skills without having any computer available in the school ICT laboratories (Acheampong & Asante, 2024). In Nigeria, the access of laboratory and digital tools on a regular basis has been a challenge to the delivery of STEM curriculum, especially in the less served areas of the country (Enugu et al., 2024). In contrast, institutions that have created cultures of innovation within their laboratories show evidence of increased student creativity, diversity in scientific thinking, and the integration of more comprehensive STEM skills. (Li et al., 2025).

Structural Inequality and Differential 4Cs Access:

According to Jamaluddin et al. (2025) digital collaborative and creative skills are also systematically affected by institutional resource constraints all across the Asia Pacific region. This is exacerbated by the gender and historical inequalities which still hinder the development of 4Cs across public universities in South Africa, as evidenced by Masset (2024) and Brioza-Valenzuela and Salas-Guzman (2024), for instance. While the European Commission (2025) acknowledged that infrastructure investment is a precondition for the implementation of 4Cs, its own recommendations are lacking in lower income setting to guide policy implementation in the absence of infrastructure. Structural infrastructure barriers are not only in the periphery but rather in the heart of 4Cs development in STEM higher education. Too many physical spaces inhibit collaboration and communication, the lack of access to key learning platforms hampers digital learning, and insufficient lab resources stifles creativity to the greatest extent.

Research Methodology

The qualitative research design using a paradigm of interpretivist was used, which is a type of research that produces knowledge through the subjective meanings and lived experiences of research participants, not through objective discovery (Pretorius, 2024; Previn & Mokhtar, 2022). To ensure transparency and trustworthiness in the process of data collection and analysis, the researcher kept a reflexive journal throughout the process, following the Braun and Clarke (2022) reflexive thematic analysis framework. (Ahmed, 2024).

Participants and Sampling Strategy:

In this study, 20 students in the Computer Science and Artificial Intelligence programs at university level participated. To ensure richness of data for the research emphasis, relevant to the researcher's focus, purposive sampling was used to deliberately

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select participants with the best information and insights to provide experience based data rather than statistical representativeness (Ahmad & Wilkins, 2024; Memon et al., 2025).

Data Collection Instrument:

The data were collected in individual semi-structured interviews, which were based on a set of pre-established questions then adapted to explore themes as they developed and offered the opportunity to give participants the freedom to describe what had happened in their own words (Ruslin et al., 2022).

Data Analysis:

The reflexive thematic analysis (RTA) framework of Braun and Clarke (2022) was used for analyzing the data. This framework is one of the most commonly used and methodologically sound approaches in qualitative data analysis (QDA) in educational and social science literature (Byrne, 2022; Ahmed, 2024).

Phase 1:

Prior to coding, all 20 transcripts were read word-for-word. The participants were first year under-graduates and second year under-graduates from BS AI, and BS CS programs of a Pakistani university and were interviewed with a 12 question structured guide that has been designed with respect to 4Cs: Critical Thinking (Q1–Q3), Collaboration (Q4–Q6), Communication (Q7–Q9) and Creativity (Q10–Q12).

Phase 2.

Initial Codes Generated All 20 transcripts were coded systematically at the semantic (explicit, surface meaning) and latent (explicatory, meaning of the text) levels.

Phase 3.

Constructing candidate themes codes were initially grouped together into themes that were deemed to be potential themes based on the patterns of shared meaning.

Phase 4.

Examine and improve themes Coded extracts as well as full transcripts were used to review candidate themes.

Phase 5.

Themes

Theme 1: about infrastructural adequacy paradox the theme reflects the juxtaposition students' reported satisfaction and identified needs for resources. There were no resource shortages in the early semester, but in the advanced and specialist equipment, there were perceived shortages, possibly due to academic naivety as a mediator in resource perception. There are a number of basic experiments covered; however, equipment is often old or limited for advanced and open-ended concepts. — P9

Theme 2: Structural barriers to collaborative engagement the three factors of timetable clashes, restricted space and large classes all contribute to non-meaningful collaboration. This is somewhat offset by informal digital tools but collaborative tools of a professional nature are missing, making these failures systemic. Large class’s group work is often given on a whim, timetables rarely agree for outside of class. P9

Theme 3: physical infrastructure problems (as in, audio-visual equipment not working) and institutional support problems. In combination, they restrict students' abilities to effectively communicate scientific results to professional audiences. For regular presentations we speak loudly, the only microphones available are for the students. P9

Theme 4: The most common theme found among all 20 participants. A lack of maker spaces, strict grading, and standardized procedures stifle experimentation. In a grade-risk chilling effect, students self-censor what they consider to be innovative approaches. Two sub-themes were identified: Constrained Autonomy and Emerging Agency. “Knowing that it could mess up your grade, then you just go along what's safe” P11

Phase 6.

Finding 1: The first finding is Infrastructural Adequacy Paradox (Critical Thinking). There was a significant difference between resource perception by year of study and program type. Early-semester students were generally pleased with the equipment that was available, although that was more as a statement of anticipation than experience as P1 commented: "I am a student of 1st semester, I have not tested them yet. Up to date equipment and limited access to high end simulators and special software are cited by advanced students for critical assessments. In fact, a practical compromise was often made to do without physical hardware, replacing it with simulation tools like Multisim, which, yet, was a limited learning environment. This is the paradox: being able to provide the tools for learning critical thinking, by itself, is not sufficient to guarantee the quality of critical thinking; pedagogical design and assessment architecture are also significant.

Finding 2: Structural Barriers to Collaborative Engagement (Collaboration) Engaging in collaboration was hindered by three overlapping barriers: issues of time, lack of physical space, and too many students per class so that teacher support is diluted.

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Coordination was not possible outside the classroom, and labs were oversubscribed during busy periods of the laboratory submission. Students resorted to WhatsApp and Google Docs as informal communication tools which were not suitable for real-time technical work because of the lack of institutional collaboration platforms. The students who did not report collaborative problems were mostly early-semester students doing simpler task-based work, indicating that structural barriers only exacerbate when meaningful collaboration is most academically important.

Finding 3: Communication Infrastructure Gaps (Communication): The communities had limited access to communication infrastructure, particularly mobile phones. There were two levels at which communication development was limited. In practice audio equipment was almost always insufficient with no microphones for regular presentations and pupils had to speak without any amplification. On the institutional level, the writing center was not staffed appropriately and was not specialized in scientific communication, which meant that students relied on individual teachers or on each other an approach that is not scalable. Most importantly, when it came to course assessment, the majority of students had little or no exposure to video, poster presentations or data visualization, with very few of these formats being used, and few students being prepared for the use of these in current professional and research settings.

Finding 4: Systemic Suppression of Creativity (Creativity) The competency most constrained by the lack of freedom was creativity, which was inhibited in three ways: no creative infrastructure, culture of procedural compliance, and the grade-risk chilling effect. The majority of the maker spaces were not accessible and were largely confined to engineering students who had to undergo semi-long training to use them, while most of the members of the group had no experience with basic fabrication tools. Most of the maker spaces were not accessible and were mostly used by engineering students who had to dedicate a semester to learning how to use them; even then, the average person who joined had very little experience in basic fabrication tools. There was little room for exploratory work to be left up to the student and fear of loss of grade was a disincentive to experimentation. P11: “Going off the script might mess up your grade it kills the urge to experiment.” This is not only a sign of a scarcity of resources, it's also a sign that there is institutional disincentive to risk taking. However, a counter narrative of adaptive agency arose as students figured out how to problem solve without the teacher's support within constraints, indicative of the creative potential of students which, however, seemed not to be structurally supported.

Thematic Map Summary

Theme	Core Barrier Type	Key Evidence (Participants)	4C Domain
1. Infrastructural Adequacy Paradox	Equipment gaps masked by novice perception	P9, P11, P20 vs P1, P2, P16	Critical Thinking
2. Structural Barriers to Collaboration	Scheduling, space, class size, tool inadequacy	P3, P6, P9, P11, P12, P13	Collaboration
3. Communication Infrastructure Gaps	Audio deficits, writing support, multimedia absence	P9, P11, P2, P18	Communication
4. Systemic Suppression of Creativity	No maker space, grade-risk deterrent, procedural culture	P9, P11, P13, P15, P18	Creativity
4a. Constrained Autonomy (sub)	Freedom within narrow procedural corridors	P6, P10, P12, P14	Critical Thinking & Creativity
4b. Emerging Agency (sub)	Student resilience and adaptive workarounds	P10, P13, P14, P15	Critical Thinking & Creativity

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Discussion:

The results highlight a systematic limitation of 4Cs development of students enrolled in higher education institutions, which is caused by infrastructure barriers. Students recognized basic resources, but a regular disparity between the actual resource and the effective adequacy was found. Critical thinking was promoted in theory, but not in practice, because of equipment limitations and obsolete tools that made it impossible to allow students to explore alternative approaches. This was due to limited space for collaboration, inflexible times, and the use of other platforms, such as WhatsApp, which were used instead of discipline-specific collaborative software, highlighting the digital divide reported by Zhang and Livingstone (2024). As found by Sarong et al. (2025), communication barriers were related to the malfunction of presentation devices and the writing center's low capacity to provide scientific reporting services. Creativity was the competency most restricted, as maker spaces, prototyping tools, and flexible assessment were all factors that inhibited experimentation, echoing Rahman et al.'s (2025) findings regarding how infrastructure challenges stifled innovation in Pakistani higher education. Together, these results support the view that the barriers of infrastructure in STEM higher education are physical and cultural, not only because of the lack of resources, but because of the institutional environment that inhibits creative and independent academic participation.

Conclusion:

This research has established that infrastructure barriers, including lack of equipment, cramped spaces, lack of maker labs, and inflexible evaluation, systematically limit critical thinking, collaboration, communication and creativity of students from STEM disciplines in higher education institutions. These barriers are not only physical, but cultural too, and help to deter independent investigation and creative risk-taking rather than simply a lack of resources. Findings indicate the need for targeted investments in advanced laboratory equipment, spaces dedicated to creative practice, and flexible timetabling, on an institutional level. Infrastructure needs to be integrated into the STEM accreditation processes, policy-wise, to facilitate equal 4Cs development. The limitations of this study stem from its single-institution design, and the fact that almost all the students were first-semesters. Need to be expanded to other institutional and geographic contexts and be combined with interviews with infrastructure audits and infrastructure investment with measurable 4Cs outcomes of STEM higher education measured by evidence-based policy frameworks.

Recommendations

- Grading frameworks should reward experimentation and process alongside outcomes, decoupling intellectual risk-taking from grade penalty to foster Critical Thinking and Creativity.
- Fabrication and prototyping facilities should be accessible across all STEM programs and embedded within curriculum requirements, not restricted to engineering cohorts.
- Scheduling should accommodate project-based collaboration through protected co-working time and reduced consecutive lecture loads, treating timetabling as a pedagogical rather than purely
- A science-specific communication center supporting technical writing, data visualization, and multimedia presentation should replace the current understaffed, general-purpose model, with multimedia formats integrated into assessed coursework.
- A longitudinal, program-wide mechanism for tracking competency development across the 4Cs beyond conventional grade metrics would enable evidence-based curriculum reform and international benchmarking.

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