



Transitions in ICT-Integrated Teaching and Learning in Trans-disciplinary STEM Education: A Systematic Review Through a Scopus Bibliometric Analysis

Vol 7, 2025



CONTACT: Judah Paul Makonye - judah.makonye@wits.ac.za

This work is licensed under a Creative Commons Attribution 4.0 International License.

Published By

The Unit for Distance Education, Faculty of Education
University of Pretoria, Groenkloof Campus
Cnr of George Storrar and Leyds Street, Pretoria, South Africa
Web address: <https://upjournals.up.ac.za/index.php/tetfle>
Email address: tetflemanager@up.ac.za
ISSN 2788-6298 (Online)

About the Journal

The Teacher Education through Flexible Learning in Africa (TETFLE) and other developing contexts online journal is a refereed, open-access e-journal that publishes original research on distance teacher education in Africa. TETFLE aims to create a platform for researchers and practitioners on glocal matters that relate to distance teacher education on the continent. Publications cover issues of content, pedagogical consideration, technology and management in distance education. Exemplar papers with rigour showing research evidence are most appreciated.

TETFLE also publishes review articles and book reviews. The journal currently appears once in a year, with an additional special edition from accepted biennial conference papers, as applicable. The journal is the official journal of the Distance Education and Teachers' Training in Africa (DETA) biennial conference, hosted by the Faculty of Education, University of Pretoria, South Africa.

Indexing

TETFLE is indexed by the Directory of Open Access Journals (DOAJ).

Editorial Team

Editor-in-chief

Folake Ruth Aluko (University of Pretoria)

Associate editors

Mary Ooko (University of Pretoria)

Marie Hyleen Mariaye (University of Mauritius)

Etinosa Olayinka (University of Pretoria)

Editors of the special issue

Dr Erasmos Charamba

National College of Ireland

[linkedin.com/in/erasmos-charamba-729105833](https://www.linkedin.com/in/erasmos-charamba-729105833)

Prof Judah Makonye

University of the Witwatersrand

City of Johannesburg, Gauteng, South Africa

[linkedin.com/in/judah-makonye-736048141](https://www.linkedin.com/in/judah-makonye-736048141)

Prof Peter Aloka

University of the Witwatersrand

City of Johannesburg, Gauteng, South Africa

[linkedin.com/in/peter-aloka-02a94a29](https://www.linkedin.com/in/peter-aloka-02a94a29)





Official publication of the Unit for Distance Education
Faculty of Education
University of Pretoria
Web address: <https://upjournals.up.ac.za/index.php/tetfle>
Email address: tetflemanager@up.ac.za

Transitions in ICT-Integrated Teaching and Learning in Trans-disciplinary STEM Education: A Systematic Review Through a Scopus Bibliometric Analysis

Judah Paul Makonye

School of Education, University of the Witwatersrand, Johannesburg

Email: judah.makonye@wits.ac.za  <https://orcid.org/0000-0001-7437-8856>

DOI: <https://doi.org/10.35293/tetfle.v7i1.5309>

Abstract

The integration of digital technologies into teaching and learning practices accelerated significantly during the COVID-19 pandemic, driving enduring pedagogical shifts that persisted beyond the pandemic. At the onset, educational institutions faced a choice: suspend curricular delivery or embrace alternative modalities to maintain instruction. Most opted for the latter, catalysing the widespread adoption of virtual technologies. Although virtual tools predated the COVID-19 pandemic, the pandemic dramatically increased their centrality in educational practice. This research is based on a systematic review of peer-reviewed literature from 2010 to 2024. Using the Substitution, Augmentation, Modification, and Redefinition (SAMR) model, this systematic study maps current pedagogical practices and interrogates the affordances and constraints of digital tools in teaching, learning, and assessment. The findings reveal incremental movement toward transformative use, but emphasise that substitution and augmentation remain dominant. The study contends that a deeper pedagogical transformation is necessary to fully harness information and communication technology (ICT) for innovative, trans-disciplinary science, technology, engineering, and mathematics (STEM) learning environments.

Keywords: Bibliometric analysis, digital learning; STEM education; pedagogical transformation.



Introduction

Back in the mid-1980s, when I was a student teacher in Zimbabwe, my mathematics lecturer, Mr Batman, would often quip, ‘A computer does not think’. Ten years on, I suggested that our teachers’ college adopt computers to enrich teaching and learning. To my surprise, a colleague dismissed the idea with laughter—a reaction that now seems emblematic of how innovation is often met with scepticism before its value becomes undeniable. Decades later, with the rise of artificial intelligence (AI), Mr Chisindi’s once-humorous remark now stands as a poignant reminder of how far we have come—and how mistaken we were about the creative potential of the Internet.

The onset of the COVID-19 pandemic precipitated an abrupt, unprecedented disruption to traditional face-to-face teaching and learning. As physical teaching and learning became perilous, the pandemic became a powerful catalyst for the rapid adoption of online teaching and learning—ushering in pedagogical innovations previously unimplemented and untested at scale (Pérez Echeverría, 2025). The much-discussed Fourth Industrial Revolution (4IR) (Philbeck & Davis, 2018) was no longer a distant theoretical prospect; it had arrived as an unignorable imperative.

Educators, whether enthusiastic adopters or reluctant participants of ICT, were compelled to engage with digital platforms for teaching, learning, and assessment. This way of teaching and learning was no longer optional, but became imperative for sustaining educational continuity (Aina & Ogegbo, 2022; Ximba, 2022). Consequently, the affordances and limitations of information and communication technologies (ICTs) in advancing educational agendas—particularly in science, technology, engineering, and mathematics (STEM) education—became a focal point of scholarly inquiry. This shift is reflected in emerging research both locally (e.g., Makhubele & Makonye, 2022) and internationally (e.g., Lukychova et al., 2022; Ah-Nam & Osman, 2017).

Across the educational spectrum—from early childhood to tertiary institutions—practitioners were faced with a stark choice: adapt to ICT-mediated instruction or risk institutional paralysis. The prohibition of face-to-face lectures, enforced through stringent government health regulations aimed at curbing viral transmission, made distance education the sole viable alternative. Unlike many years ago, when distance tuition occurred via hard-copy correspondence through post offices, as at the University of South Africa (UNISA), digital methods are now within easy reach. For many, ICT had previously been perceived as a peripheral or supplementary tool, often

deferred or dismissed. The pandemic, however, redefined their role as central to the survival and evolution of educational practice.

Interdisciplinary STEM education is a pedagogical approach that integrates science, technology, engineering, and mathematics to address complex, real-world problems by synthesising knowledge and skills across disciplinary boundaries (Makonye, 2022). Rather than teaching these subjects in isolation, interdisciplinary STEM education fosters holistic learning environments in which students recognise the interconnections and interdependencies among STEM domains (English, 2016). This approach cultivates collaboration, critical thinking, creativity, and problem-solving, as learners engage in projects that require them to draw upon diverse disciplinary methods and perspectives (Tytler et al., 2021). By embedding interdisciplinary strategies within STEM curricula, educators better prepare students for the demands of contemporary society, where multifaceted challenges necessitate integrated expertise and adaptive reasoning (NAE & NRC, 2014). Such pedagogical models promote a comprehensive understanding of how STEM fields interact, equipping learners with the cognitive flexibility and collaborative skills essential for innovation and lifelong learning.

The current study investigates the pedagogical transformations evident in a systematic review of research on ICT integration in transdisciplinary STEM education. It critically examines the emergent computer skill sets and competencies required to navigate shifts in trans-disciplinary STEM education pedagogy and assessment. The central research question guiding this inquiry is: Based on reviewed literature in trans-disciplinary STEM education, what constraints and affordances associated with ICT use in mathematics and science teacher education can be identified to inform transformation in virtual learning spaces?

To address this question, the study explores teaching, learning, and assessment practices through the analytical lens of the Substitution, Augmentation, Modification, and Redefinition (SAMR) model (Puentadura, 2012) as a framework for evaluating the depth and impact of ICT integration.

Theoretical framework

Granted that education is an acculturation and enculturation process sustaining humanity (Bishop, 1988; Vygotsky & Cole, 1978), what theories may explain change in teaching and learning when ICT tools are used to replace or blend with the face-to-face traditional teaching approaches that are no longer sufficient in the 4IR age? I



propose that the use of technology in teaching and learning can be viewed through the lens of the sociocultural perspective, where learning is psychologically mediated by signs and tools (Vygotsky & Cole, 1978), such as virtual artifacts of ICT.

Since the onset of ICT in education, researchers have sought theoretical settings to map that pedagogical process. To the author, the theoretical framework that can further assist in studying the harnessing of technology in pedagogy is the SAMR (Substitution, Augmentation, Modification, Redefinition) model (Puentedura, 2012) (see Figure 1).

| Level | Category | Description |
|-----------------------|--------------|---|
| Transformation | Redefinition | Tech allows for the creation of new tasks, previously inconceivable |
| | Modification | Tech allows for significant task redesign |
| Enhancement | Augmentation | Tech acts as a direct tool substitute, with functional improvement |
| | Substitution | Tech acts as a direct tool substitute, with no functional change |

Figure 1: The SAMR Mode, adapted from Puentedura (2012)

The SAMR model explains the various stages and evolution of technology use in teaching and learning. The first stage is where technology is used to enable students to access learning materials; that is, simply substituting for traditional teaching roles, such as giving texts, workbooks, and exercises—hard copy transformed into soft copy, such as a textbook in PDF form. Another example is writing an essay using a word processor instead of a ballpoint pen and paper, or learners doing a long multiplication sum using a computer calculator app such as Symbolab in lieu of pencil and paper. The next stage is the augmentation level, when technology is used to enhance functionality, such as online direct learner feedback for STEM tasks, thereby improving participation. This is an improvement on the traditional situation where students would do the written work in exercise books, then submit it to the teacher, wait for the teacher to mark and assess it, and return it later. Another example of substitution is a teacher recording their mathematics lesson and sharing it on WhatsApp with students. The ICT augmentation stage is very personal and gives rapid feedback. The teacher's main efforts are setting up the work for learners to do, and monitoring the feedback. An example of augmentation in STEM education is when students use a simulation to observe basic circuits with adjustable voltage inputs.

As learners receive rapid feedback when they vary their inputs, they can observe patterns more easily. Immediate feedback on when they are right or wrong can motivate them to strengthen productive thinking and reconsider their misconceptions. This can be referred to as Computer-Assisted Instruction (CAI) (Panjay, 2023). CAI refers to teaching or remediation done via a computer app; it is often interactive and produces immediate feedback. CAI supports personalised learning and enhances student participation and expertise acquisition. The first two stages of the SAMR model, substitution and augmentation, can be viewed as an enhancement of traditional face-to-face teaching. At these stages, learners become more comfortable using digital tools, however, the old ways of teaching and learning only change in mode, not in function. The next two stages are functionally different.

In the modification stage, technology allows for significant task redesign. Here, common tasks are not only accomplished through technology; students also engage more with one another as they share knowledge and problem-solving approaches. Students can participate and interact across time and space, and multimedia can be used. In these situations, teachers and students from different schools can work together to solve STEM problems. The use of Zoom or Microsoft Teams Apps enhances that. Clearly, it was not possible for geographically dispersed students and teachers to collaborate on learning in real time. This is a change of game. The highest stage is the redefinition stage, where previously inconceivable tasks, as well as teaching and learning, are now made available by technology. The emergence of artificial intelligence (AI) sits at the redefinition level. It will revolutionise and escalate pedagogical integration in unimagined ways. An example is learners sharing problems and solutions at a global stage. I do not doubt that AI will make knowledge accessible to everyone in the world. That way, untapped talent from many undeveloped parts of the world will be shared globally, leading to exponential growth of STEM knowledge. Thus, the SAMR model shows the escalation of technology use in teaching and learning. It explains the shift in the use of technology in education from rituals and routine learning to exploration (Sfard, 2016), which lies at the heart of educational transformation and learning. The last two stages represent transformative teaching and learning—a departure from the traditional teaching and learning methods that have been used for many years.



In examining the transitions in ICT integration within trans-disciplinary STEM education, this study researched the following questions:

1. With respect to the SAMR model, how has ICT integration evolved in trans-disciplinary STEM education between 2010 and 2024?
2. In what ways can the SAMR model be applied to evaluate or guide technology-enhanced teaching and learning in trans-disciplinary STEM education?
3. What trends, challenges, and innovations characterise the transition from enhancement to transformation stages of using ICTs in trans-disciplinary STEM education?

Contribution of the paper to the field

This article contributes to understanding the trends from 2010 to 2024 in the integration of ICT within trans-disciplinary STEM education. It informs researchers and STEM education policymakers on the way forward for implementing curriculum reforms in the era of ubiquitous virtual educational capabilities that must be harnessed to enhance teaching and learning. The importance of this research lies in its ability to highlight where ICT integration remains at a basic level, where transformation is beginning to occur, and how the SAMR model can guide future practice. By situating the findings within both theoretical frameworks and literature, the study provides evidence-based insights that can shape professional development, curriculum revision, and assessment innovation. In this way, the research shows the urgency of moving beyond basic ICT use to transformative use in STEM education.

Literature review on STEM education

Since around 2010, research using the SAMR model, STEM education, focusing on science, technology, engineering, and mathematics pedagogy, has gained significant impetus due to its central role in preparing learners for the demands of a rapidly evolving world. The continuous advancement of digital technologies, now embodied by the marvel of AI, calls for the effective integration of technology into educational processes.

Dzulkarnain et al., (2021) investigated student engagement in a university-level STEM course through a digital video project. Using the SAMR model as a lens, the study assessed how varying levels of ICT integration influenced teaching and learning practices. The research involved two groups: a treatment group engaged in

the digital video project and a control group taught via traditional lecture methods. Findings indicated that the treatment group demonstrated significantly higher levels of engagement and ICT integration, suggesting that technology-enhanced pedagogies can positively impact learner outcomes.

In a separate study, Dey (2017) examined the use of the SAMR model in flipped STEM classrooms, focusing on how technology integration influences student motivation, engagement, and learning in blended environments. The study contributed to a deeper understanding of how the SAMR framework can be applied to evaluate ICT-mediated learning experiences and pedagogical shifts. Romrell et al. (2014) explored the role of mobile devices in transforming classroom learning. As mobile technologies become increasingly embedded in students' lives, their potential to support personalised, situated, and connected learning—referred to as mobile learning (mLearning)—has grown. The authors applied the SAMR model to categorise mLearning activities and assess their pedagogical impact. The work by Romrell et al. (2014) highlighted both the opportunities and challenges of implementing mobile technologies in education, emphasising the need for structured frameworks to guide effective integration.

Aduyasas (2021) conducted a study involving 60 students to examine the effects of integrating ICT within a learning community and a lesson study approach in mathematics education. The research employed both the SAMR and Technological Pedagogical Content Knowledge (TPACK) models to guide and evaluate the integration of technology, pedagogy, and content knowledge. The SAMR framework was instrumental in mapping the levels of technological integration across instructional practices, offering insights into how digital tools can enhance learner outcomes when strategically applied.

All the studies discussed above, while having different foci and samples, demonstrate the effectiveness of the SAMR model in understanding how ICT-mediated educational processes can be better understood. Thus, the SAMR model shows potential for investigating interdisciplinary STEM education research from 2010 to 2024. Thus, among the frameworks developed to guide ICT integration, the SAMR model (Puentedura, 2012) stands out for its clarity and applicability in evaluating the depth of ICT use in teaching and learning, such as in Transdisciplinary STEM Education.



Methodology

This systematic review explores advancements in STEM education research in ICT and uses the SAMR model as a lens for the study. A qualitative research design (Yin, 2009) was conducted using the Scopus database to identify relevant research articles on ICT integration in STEM education. In this systematic review examining transitions in ICT-integrated teaching and learning within trans-disciplinary STEM education (2010–2024), the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) were employed to ensure methodological transparency, consistency, and replicability. PRISMA provides a structured approach for reporting systematic reviews and meta-analyses, including a 27-item checklist and a flow diagram that traces the identification, screening, eligibility, and inclusion of studies. By applying PRISMA, this review systematically documents the search strategy, inclusion/exclusion criteria, and synthesis process, particularly in relation to the SAMR model's application across STEM contexts. This approach enhances the credibility of the findings and supports evidence-based insights into how digital technologies have transitioned from enhancement to transformation stages in educational practice.

Using the Scopus database, the search used the following strings:

(“ICT integration” OR “technology-enhanced learning” OR “digital pedagogy” OR “educational technology”);

(“STEM education” OR “trans-disciplinary learning” OR “interdisciplinary STEM” OR “cross-disciplinary education”);

(“SAMR model” OR “substitution augmentation modification redefinition” OR “technology integration framework”).

The combined search string was:

TITLE-ABS-KEY (“*ICT integration*” OR “*educational technology*”) AND

TITLE-ABS-KEY (“*STEM education*” OR “*transdisciplinary learning*”) AND

TITLE-ABS-KEY (“*SAMR model*”) AND

PUBYEAR > 2010 AND PUBYEAR < 2024

In systematic research, using the PRISMA approach promotes transparency and replicability of the research, which enhances its credibility.

In the current study on ICT-integrated STEM education, PRISMA offered a rigorous scaffold that documents search strategy, inclusion criteria, and synthesis when evaluating transitions across SAMR stages.

Data analysis

This study employed a structured literature analysis to examine ICT integration in trans-disciplinary STEM education, focusing on teaching, learning, and assessment practices. Data were extracted from the Scopus database, which offers comprehensive coverage of peer-reviewed publications across global research domains. Selected articles were systematically reviewed and categorised according to pedagogical dimensions aligned with the SAMR framework.

Tables 1 to 5 present a synthesis of the reviewed literature, organised into three thematic categories: teacher actions; student actions; and assessment actions in trans-disciplinary STEM education research. This classification enables an embedded understanding of how ICT tools are operationalised across instructional roles and learning processes. The analysis followed a qualitative content-mapping approach, identifying patterns of technology use and pedagogical transformation within each SAMR level, as recommended in Bibliometric and thematic reviews of STEM education research (Chehlarova et al., 2023).

The following Table 1 provides frequencies of teacher actions in trans-disciplinary STEM education research

Table 1: Teacher actions in transdisciplinary STEM education

| Teacher Actions | S | A | M | R | Total | Publications |
|--------------------------|----|----|---|---|-------|--|
| Create activities | 9 | 21 | 2 | 4 | 36 | 12, 13, 16, 19, 20, 23, 31, 34, 38, 46, 58, 62, 64, 70, 74, 125, 130, 132, 134, 135, 152, 159, 160, 161, 164, 172, 189, 196, 201, 216 |
| Present content | 26 | 4 | 2 | 0 | 32 | 6, 17, 66, 74, 76, 86, 87, 92, 104, 108, 111, 118, 121, 122, 126, 127, 136, 148, 158, 161, 164, 167, 169, 184, 189, 195, 201, 207, 209, 213, 215 |

| Teacher Actions | S | A | M | R | Total | Publications |
|---|----|---|---|---|-------|--|
| Share materials | 12 | 9 | 0 | 0 | 21 | 4, 12, 20, 31, 39, 70, 83, 91, 101, 111, 134, 166, 172, 174, 177, 189, 194 |
| Communicate | 15 | 3 | 1 | 1 | 20 | 1, 2, 3, 4, 7, 16, 17, 20, 31, 39, 53, 74, 82, 145, 152, 162, 194 |
| Collaborate | 0 | 0 | 0 | 5 | 5 | 36, 47, 53, 55, 111 |
| Set activities | 1 | 3 | 0 | 0 | 4 | 61, 86, 101, 210 |
| Change in ownership (teacher → student) | 0 | 1 | 0 | 0 | 1 | 130 |
| Co-construction (teacher & student) | 0 | 0 | 1 | 0 | 1 | 169 |
| Flipped learning | 0 | 0 | 1 | 0 | 1 | 24 |
| Reflect on practice | 0 | 0 | 1 | 0 | 1 | 137 |
| Use for administrative purposes | 1 | 0 | 0 | 0 | 1 | 152 |

Source: Scopus database

On selected teacher actions, Table 1 reflects the integration in transdisciplinary STEM education in enhancement and transformation.

Table 2: Selected teacher actions in ICT integration in transdisciplinary STEM education

| | Enhancement | Transformation |
|---------------------------------|-------------|----------------|
| Create Activities | 30 | 6 |
| Present Content | 30 | 2 |
| Share Materials and Communicate | 39 | 2 |
| Collaborate | 0 | 5 |
| Total | 99 | 15 |

The totals of the above data are visually represented in Figure 2.

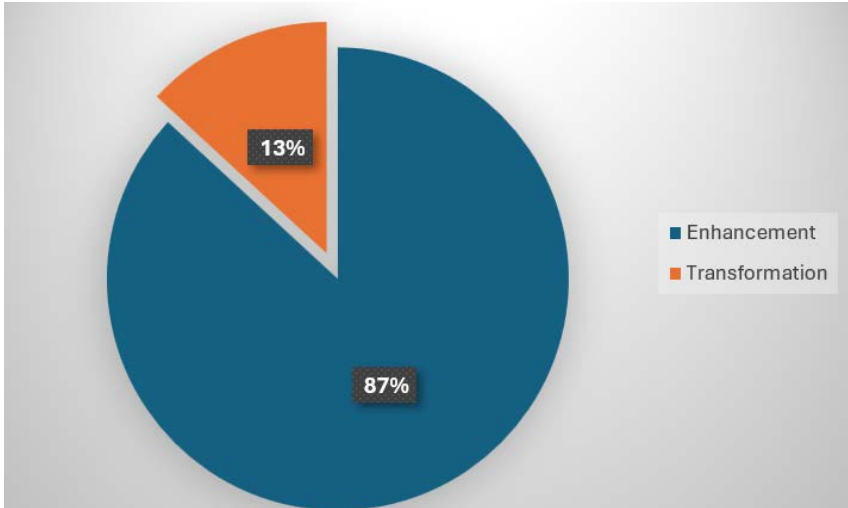


Figure 2: Comparison between enhancing (S, A) and transformative (M, R) ICT teacher activities in STEM classes

Source: Author's own

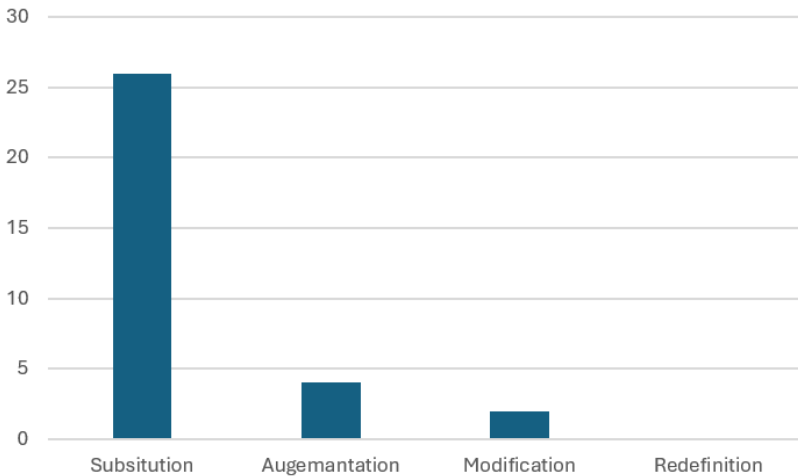


Figure 3: Teacher Action: Create Activities with ICT- SAMR levels

Source: Author's own



CONTACT: Judah Paul Makonye - judah.makonye@wits.ac.za

This work is licensed under a Creative Commons Attribution 4.0 International License.

The data show that teacher actions remain largely replicative, with a pronounced reliance on traditional instructional approaches. Most activities observed align predominantly with the substitution level of the SAMR model, indicating minimal pedagogical transformation. While instances of modification are present, they are relatively limited. Notably, there is a complete absence of practices corresponding to the redefinition stage, suggesting that the transformative use of ICT to create previously inconceivable learning experiences has yet to be realised in teacher-led initiatives.

The following Table 3 shows the frequencies of student actions in ICT use in transdisciplinary STEM education research.

Table 3: Student actions in ICT integration in transdisciplinary STEM education

| Student Actions | S | A | M | R | Total | Publications |
|-------------------------------------|----|----|---|---|-------|--|
| Access content | 20 | 3 | 0 | 0 | 23 | 6, 17, 66, 74, 76, 86, 87, 92, 104, 108, 111, 118, 121, 122, 126, 127, 136, 148, 158, 161, 164, 167, 169 |
| Submit work | 11 | 3 | 0 | 0 | 14 | 4, 12, 20, 31, 39, 70, 83, 91, 101, 111, 134, 166, 172, 174 |
| Communicate | 10 | 3 | 1 | 1 | 15 | 1, 2, 3, 4, 7, 16, 17, 20, 31, 39, 53, 74, 82, 145, 152 |
| Create content | 5 | 13 | 2 | 4 | 24 | 12, 13, 16, 19, 20, 23, 31, 34, 38, 46, 58, 62, 64, 70, 74, 125, 130, 132, 134, 135, 152, 159, 160, 161 |
| Collaborate | 0 | 0 | 0 | 5 | 5 | 36, 47, 53, 55, 111 |
| Co-construction (student & teacher) | 0 | 0 | 1 | 0 | 1 | 169 |
| Flipped learning | 0 | 0 | 1 | 0 | 1 | 24 |
| Reflect on learning | 0 | 0 | 1 | 0 | 1 | 137 |
| Use for administrative purposes | 1 | 0 | 0 | 0 | 1 | 152 |

Source: Scopus database

On selected student actions, Table 4 reflects the substitution and reformulation on selected student actions.

Table 4: Frequency of substitution (lowest level) and reformulation (highest level)

| | Substitution | Reformulation |
|-----------------------------------|--------------|---------------|
| Complete Set of Activities | 108 | 13 |
| Access Content | 37 | 1 |
| Collaborate | 0 | 5 |

The above data is shown in Figure 4 below as percentages.

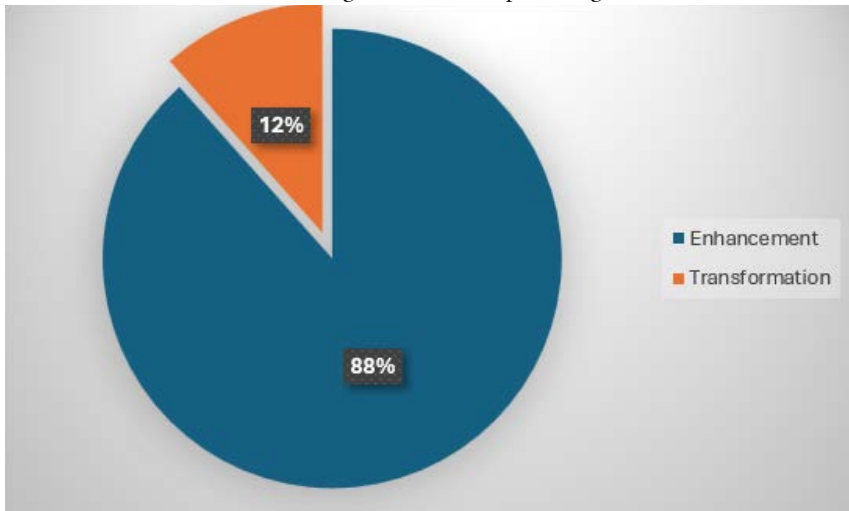


Figure 4: Comparison between enhancing (S, A) and transformative (M, R) ICT student activities in STEM classes

Source: Author's own

The following Table 5 shows the frequencies of assessment actions in ICT use in transdisciplinary STEM education research.

Table 5: Assessment actions in ICT use in transdisciplinary STEM education

| Student Actions | S | A | M | R | Total | Publications |
|--|----------|----------|----------|----------|--------------|--|
| Access content | 20 | 3 | 0 | 0 | 23 | 6, 17, 66, 74, 76, 86, 87, 92, 104, 108, 111, 118, 121, 122, 126, 127, 136, 148, 158, 161, 164, 167, 169 |
| Submit work | 11 | 3 | 0 | 0 | 14 | 4, 12, 20, 31, 39, 70, 83, 91, 101, 111, 134, 166, 172, 174 |
| Communicate | 10 | 3 | 1 | 1 | 15 | 1, 2, 3, 4, 7, 16, 17, 20, 31, 39, 53, 74, 82, 145, 152 |
| Create content | 5 | 13 | 2 | 4 | 24 | 12, 13, 16, 19, 20, 23, 31, 34, 38, 46, 58, 62, 64, 70, 74, 125, 130, 132, 134, 135, 152, 159, 160, 161 |
| Collaborate | 0 | 0 | 0 | 5 | 5 | 36, 47, 53, 55, 111 |
| Co-construction (student & teacher) | 0 | 0 | 1 | 0 | 1 | 169 |
| Flipped learning | 0 | 0 | 1 | 0 | 1 | 24 |
| Reflect on learning | 0 | 0 | 1 | 0 | 1 | 137 |
| Use for administrative purposes | 1 | 0 | 0 | 0 | 1 | 152 |

Source: Scopus database

The Figure 5 shows a strong trend toward more digital forms of assessment in transdisciplinary STEM education.

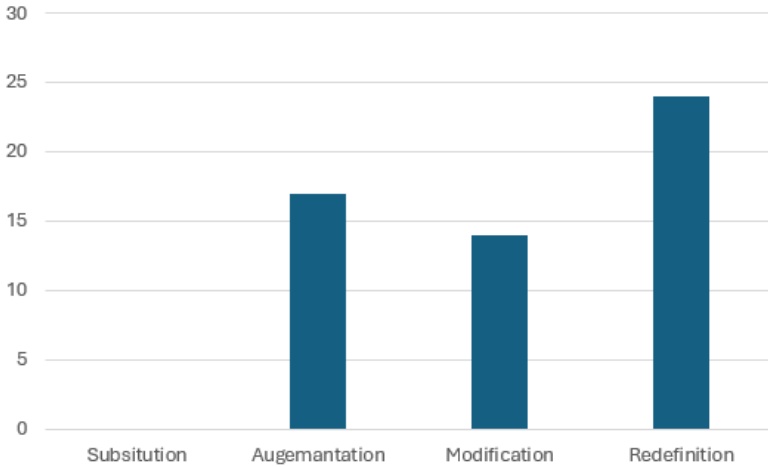


Figure 5: Assessment: Project-based, inquiry-based, and independent learning

Source: Author's own

Figure 6 shows that in assessments, students moved away from the lower levels of SAMR to self-regulated learning when project work assessments were more frequent.

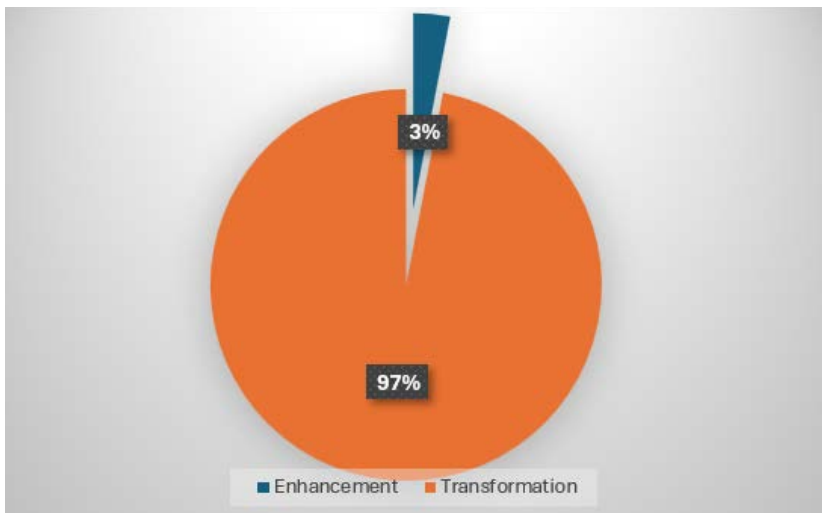


Figure 6: Comparison between enhancing (S, A) and transformative (M, R) ICT assessments

Source: Author's own



CONTACT: Judah Paul Makonye - judah.makonye@wits.ac.za

This work is licensed under a Creative Commons Attribution 4.0 International License.

From the above findings, the study proceeds to the discussion, in which the results are analysed considering the theoretical framework and the literature reviewed. The SAMR model (Puentedura, 2012) provides the central lens. In addition, Vygotsky and Cole's (1978) sociocultural theory offers explanatory power by showing how ICT tools act as mediating artefacts that either replicate or transform pedagogical practices.

Discussion

The onset of ICT integration in STEM education has been uneven, reflecting both opportunities and constraints. As Vygotsky and Cole (1978) posit, learning is mediated by signs and tools in both inter-psychological and intra-psychological contexts. In the era of the ubiquitous 4IR now upon us, teaching and learning increasingly occur through digital artifacts, represented by ubiquitous ICT tools integral to everyday life.

With respect to the first research question on ICT integration evolution in transdisciplinary STEM education between 2010 and 2024, the findings from the current study reveal varied patterns of ICT integration across teacher, student, and assessment actions. Teacher practices were found to mainly align with the substitution and augmentation levels, with 99 enhancement actions compared to only 15 transformative ones. This shows that nearly 87% of teacher activities remain replicative, digitising traditional pedagogies rather than redesigning them. This mirrors what Sfard (2016) describes as ritual learning, in which technology reproduces established routines without enabling exploration.

Also, student actions occur at all levels of the SAMR model, though they are more concentrated at the lower end, with 88% of student engagement remaining at the substitution and augmentation stages. Students' collaborative projects and inquiry-based learning—though less frequent—demonstrate the upper modifications and redefinitions stage. This was argued by Romrell et al., (2014), who found that mobile learning fosters personalised and connected experiences.

In the current study, assessment actions aligned more closely with the higher levels of the SAMR model. There were 32 transformative actions compared to only one for enhancement. Thus, assessment emerges as the domain most advanced in ICT integration. There were many project-based and inquiry-driven assessments that illustrated how ICT enables self-regulated learning and multimedia documentation, consistent with the findings of Dzulkarnain et al. (2021), that video-based projects enhanced engagement and learning.

The second research question concerned how the SAMR model was applied to evaluate or guide technology-enhanced teaching and learning in trans-disciplinary STEM education.

The SAMR model proved instrumental for theorising and categorising ICT integration, offering a clearly structured lens for assessing ICT pedagogical transformation. At the lower levels, ICT tools function as mediating artifacts (Vygotsky & Cole, 1978), extending existing routines without fundamentally altering pedagogy. Examples include digitised worksheets, recorded lessons, or WhatsApp sharing of teaching and learning materials.

At the modification stage, ICT enables significant task redesign. Students can collaborate across time and space, using platforms like Zoom or Teams, which was not possible in traditional classrooms. At the redefinition stage, previously inconceivable tasks become possible, such as global collaboration and AI-mediated learning. This resonates with Adulyasas (2021), who emphasised that SAMR and TPACK frameworks are critical for guiding integration beyond augmentation. Student collaboration at reformulation demonstrated how ICT mediates peer-to-peer knowledge construction, consistent with the findings of Romrell et al. (2014). Assessment practices, particularly at the modification and redefinition levels, demonstrate how the SAMR framework can guide educators in designing tasks that leverage ICT for transformative learning.

Next, we discuss research question 3 on trends, challenges, and innovations that characterise the transition from the enhancement to the transformation stages of using ICTs in trans-disciplinary STEM education. The findings show that teachers are struggling to shed old teaching methodologies for STEM subjects. Teachers are still bound by yesterday's pedagogies—old habits die hard, proving that old success is a barrier to development. Teacher actions remained largely replicative, underlined by traditional instructional approaches, indicating negligible pedagogical transformation.

Student actions on the scale, though more varied, still concentrate at the lower end of the SAMR model. Collaborative projects and inquiry-based learning—though less frequent—demonstrate modifications and redefinitions emerging. This distribution suggests that learners are beginning to engage with ICTs in more transformative ways, albeit inconsistently.

By contrast, assessment practices show a stronger alignment with transformative practices. Project-based learning, peer feedback, and multimedia documentation reflect modification and redefinition, indicating that assessment is emerging as a



domain where ICT integration is more advanced and transformative. This resonates with Adulyasas (2021), who emphasised that frameworks such as SAMR and TPACK are critical for guiding integration beyond mere augmentation.

The transformative use of ICT in trans-disciplinary STEM education has been shown to increase student engagement, particularly when technologies are employed at the higher levels. These levels foster interaction not only with content, but also among learners, heightening collaboration, creativity, and intrinsic motivation (Dey, 2017). Furthermore, ICT integration is seen as supportive of the development of problem-solving skills, as it enables learners to access diverse resources, engage in self-directed inquiry (Makonye, 2015; Makonye & Sulisworo, 2025), and engage in continuous learning beyond the classroom.

Thus, ICT integration in transdisciplinary STEM education remains predominantly at the enhancement stage, with uneven progress toward transformation. Yet, the evidence of modification and redefinition in student collaboration and assessment demonstrates the emerging transformative potential of ICT. Interpreted through Vygotsky's sociocultural lens, ICT tools primarily function as mediating artifacts that extend existing routines rather than fundamentally altering them.

Conclusion

The SAMR model provides a framework for both evaluating ICT integration in transdisciplinary STEM educational practices and a roadmap for guiding future integration toward genuinely transformative STEM education. In this article, it proved instrumental in categorising ICT integration, offering a structured lens for assessing pedagogical transformation. The evidence suggests that ICT integration remains predominantly at the enhancement stage, with only incremental progress toward transformation, particularly in assessment practices. To move forward, STEM curricula should be revised to promote pedagogical practices that align with the higher levels of the SAMR model—modification and redefinition. Teachers require ongoing professional development and targeted training in the use of ICT for lesson design, enabling them to enhance their pedagogical practice in ways that move beyond simply digitising traditional tasks. Assessment innovation, which already demonstrates stronger movement toward transformation, should be leveraged as a catalyst for broader pedagogical change, expanding project-based and inquiry-driven formats that foster self-regulated learning and collaboration.

Given that ICT integration in transdisciplinary STEM education is progressing unevenly, if curricula are revised, teachers are supported, and assessment innovations are expanded, ICT can serve not merely as a coping mechanism, but also as a driver of enduring educational transformation in the AI age. Research on ICT integration in trans-disciplinary STEM education should focus on moving teaching and learning beyond enhancement stages into the transformative levels of the SAMR model. Future studies should explore strategies that enable consistent engagement in modification and redefinition, where ICT fosters collaboration, creativity, and problem-solving.

Limitations of the study

This study used bibliometric analysis of articles published exclusively in the Scopus database. This presents a limitation, as research outputs from other databases, conferences, or books were not included in the analysis. Nevertheless, the impact of this research remains significant, because Scopus is one of the most important academic databases, capturing studies from many of the field's most prominent scholars. Furthermore, the study can be regarded as a case study, which is valuable as a qualitative inquiry, offering insights into the trends and patterns of ICT integration in trans-disciplinary STEM education.

Acknowledgements

The author acknowledges the assistance of AI, namely Copilot, in the development of this manuscript, specifically in articulating aspects of the research design—most notably the elaboration of the PRISMA approach. Grammarly and Manuscript.ai aided with language editing and proofreading to enhance the overall flow and clarity of the text. All other contributions, including the conceptualisation of the study and the substantive writing, are entirely the author's own.

References

- Adulyasas, L. (2021). The use of learning community incorporating with lesson study in teaching and learning mathematics through TPACK and SAMR model: The effects on students' mathematics achievement. *Psychology Education Journal*, 58(1), 1704-1711.
- Ah-Nam, L., & Osman, K. (2017). Developing 21st century skills through a constructivist-constructionist learning environment. *K-12 Stem Education*, 3(2), 205-216.



- Aina, A. Y., & Ogebo, A. A. (2022). Investigating TVET college educators' experiences while transitioning from the traditional classroom to the virtual classroom during the COVID-19 pandemic. *Perspectives in Education*, 40(1), 129-142. <https://journals.ufs.ac.za/index.php/pie/article/download/5301/4361/14794>
- Bishop, A. J. (1988). *Mathematics education and culture*. Dordrecht: Kluwer Academic Publishers.
- Cehlarova, T., Cehlarov, S., & Nikolova, E. (2023). Bibliometric and thematic reviews of STEM education research. *Journal of Mathematics Education*, 16(2), 45-62.
- Philbeck, T., & Davis, N. (2018). The fourth industrial revolution. *Journal of International Affairs*, 72(1), 17-22.
- Dey, A. (2017). Flipped classrooms and the SAMR model: A study of student motivation and engagement. *Journal of Educational Technology Development and Exchange*, 10(1), 1-15.
- Dzulkarnain, I., Aziz, N. A. A., & El Khuluqo, I. (2021, May). Student Engagement in University STEM Course Through Digital Video Project Using SAMR Model. In *1st Annual International Conference on Natural and Social Science Education (ICNSSE 2020)* (pp. 49-57). Atlantis Press.
- English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education*, 3(3), 1-8. <https://doi.org/10.1186/s40594-016-0036-1>
- Grammarly. (n.d.). Grammarly [AI-powered writing assistant]. Grammarly Inc. <https://www.grammarly.com>
- Lukychova, N. S., Osypova, N. V., & Yuzbasheva, G. S. (2022). ICT and current trends as a path to STEM education: Implementation and prospects. *CTE Workshop Proceedings*, 9, 39-55. CEUR-WS.org. <https://doi.org/10.55056/cte.100>
- Makonye, J. (2015). Understanding of Grade 10 learner errors and misconceptions in elementary algebra. *Journal of Educational Studies*, 2015(si-1), 288-313. eMakhubele, J. C., & Makonye, J. P. (2022). ICT integration in mathematics teacher education. *African Journal of Teacher Education and Development*, 4(1), 55-72.
- Sulisworo, D., & Makonye, J. P. (2025). ICT integration and problem-solving in STEM classrooms. *Journal of STEM Pedagogy*, 8(1), 22-39.
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: *The PRISMA statement*. *PLoS Medicine*, 6(7), e1000097. <https://doi.org/10.1371/journal.pmed.1000097>

- National Academy of Engineering (NAE) & National Research Council (NRC). (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press.
- Panjay, R. (2023). Computer-assisted instruction in mathematics education. *Journal of Digital Pedagogy*, 5(2), 77–89.
- Puentedura, R. R. (2012). Technology in education: The first 200,000 years. In *The NMC Perspective Series: Ideas that Matter. NMC Summer Conference. Creative Commons*.
- Romrell, D., Kidder, L., & Wood, E. (2014). The SAMR model as a framework for evaluating mLearning. *Online Learning Journal*, 18(2), 1–15.
- Sfard, A. (2016). Ritual and exploration in mathematics learning. *Educational Studies in Mathematics*, 91(1), 1–14. <https://doi.org/10.1007/s10649-015-9639-6>
- Tytler, R., Mulligan, J., Prain, V., White, P., Xu, L., Kirk, M., Nielsen, C., & Speldewinde, C. (2021). An interdisciplinary approach to primary school mathematics and science learning. *International Journal of Science Education*, 43(12), 1926–1949. <https://doi.org/10.1080/09500693.2021.1932950>
- Vygotsky, L. S., & Cole, M. (1978). *Mind in society: Development of higher psychological processes*. Cambridge, MA: Harvard University Press.
- Ximba, B. (2022). ICT integration in secondary school STEM education. *Journal of Science Education*, 18(3), 211–225.
- Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). Thousand Oaks, CA: Sage Publications.

