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Integrating Sustainable Development and 4IR Competencies in South African Mathematics Education: A Rural Secondary School Perspective

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Abstract. The rapid evolution of the Fourth Industrial Revolution has catalysed a global reimagining of education systems, with mathematics education positioned as central to equipping learners with the critical competencies required for sustainable development. This study explored how selected South African secondary schools integrate sustainable development principles and 4IR-aligned competencies into mathematics education. Amidst ongoing socio-economic inequalities, digital divides, and limited teacher preparedness in under-resourced contexts, the study interrogated the pedagogical approaches, technological infrastructure, and stakeholder collaborations that influence the integration of sustainability into the mathematics curriculum. Anchored in Human Capital Theory, Constructivist Theory, Social Constructivist Theory, Sustainability Education Theory and TPACK, the study conceptualised education as a strategic investment that enhances learner productivity, employability, and the capacity to contribute meaningfully to national development. From this perspective, mathematics education is a conduit for cultivating problem-solving, analytical reasoning, and data literacy, skills essential for navigating the complexities of the 4IR and advancing sustainable futures. A qualitative case study design focused on selected rural and peri-urban South African secondary schools. The data was collected through semi-structured interviews, classroom observations, and document analysis to gain insights into teacher practices, resource availability, and curriculum responsiveness. The findings revealed a misalignment between policy intentions and classroom realities, with limited integration of sustainability themes, infrastructural inadequacies, and insufficient teacher training. However, innovative grassroots practices and emerging community partnerships offer potential entry points for reform. The study recommends targeted professional development, investment in digital infrastructure, and systemic support to foster a contextually relevant, sustainability-driven mathematics education responsive to 4IR demands.

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1. Introduction

The integration of sustainable development into mathematics education has become an urgent global priority, particularly under the influence of the Fourth Industrial Revolution (4IR). The 4IR, driven by advanced technologies such as artificial intelligence, robotics, machine learning, and big data, is transforming economies, societies, and education systems worldwide (Ampo et al., 2025; Hossain, 2023). As a result, educational frameworks increasingly emphasise competencies such as critical thinking, data literacy, systems thinking, and advanced problem-solving, all of which are inherently connected to mathematics education (Sujatha & Vinayakan, 2023).

Globally, there is a growing consensus on reconceptualising mathematics education to address sustainable development goals (SDGs). Research by Vásquez et al. (2023) highlighted the need to embed real-world applications in mathematics and statistics to tackle ecological, social, and economic challenges. Mathematical modelling, statistical reasoning, and computational thinking are essential for enabling learners to understand climate change, manage resources, and evaluate inclusive development strategies. Rico et al. (2021) further noted that teaching abstract mathematics through a sustainability lens enhances conceptual understanding while promoting its meaningful application.

Regional studies reinforce these perspectives. In Uganda, Okello and Nsubuga (2023) argued for integrating sustainable development and 4IR skills into mathematics to address issues such as environmental degradation and youth unemployment. Batiibwe (2024) advocates for constructivist and ethnomathematics approaches to link mathematical learning with cultural and ecological contexts. While Darbellay (2024) said that these innovations are promising, challenges remain, including inadequate teacher training, limited interdisciplinary collaboration, and resource constraints.

In South Africa, the drive to align mathematics education with 21st-century skills intersects with deep systemic inequalities. Although the Department of Basic Education has initiated curriculum reforms referencing sustainability and 4IR priorities (Kaziya, 2025; Motseki & Sophy, 2024), integration remains fragmented. Rural and peri-urban schools face acute challenges such as poor infrastructure, a shortage of qualified mathematics teachers, limited access to digital tools, and insufficient professional development (Mughal, 2024).

According to Miah (2024), this digital and pedagogical divide exacerbates disparities in learning outcomes. Technological innovations such as blended learning platforms, interactive geometry tools, and 3D modelling software can enhance mathematics teaching for sustainability, but they require systemic investment, supportive policies, and teacher training (Cirneanu & Moldoveanu, 2024). Studies show that mathematics education can embed Education for Sustainable Development (ESD) through contextualised tasks and indigenous knowledge, while aligning with Fourth Industrial Revolution (4IR) skills like coding, data handling, and modelling. However, rural and disadvantaged schools in South Africa continue to face barriers such as poor infrastructure, inadequate digital resources, teacher capacity gaps, and language challenges. These gaps highlight the need for context-sensitive, evidence-based strategies that move beyond conceptual frameworks to address the realities of rural secondary schools.

To address this gap, the present study investigates how selected South African secondary schools integrate sustainability principles and 4IR-related skills into mathematics education. Guided by **Constructivist Learning Theory**, which emphasises the learners' active engagement and contextual knowledge construction, this study explores pedagogical approaches, teacher readiness, infrastructural conditions, and community partnerships. The following research questions frame the study:

1. How are sustainability principles and 4IR competencies currently integrated into mathematics education in the selected South African secondary schools?
2. What pedagogical strategies and resources do teachers use to promote sustainability-focused mathematics learning?
3. What infrastructural and professional development challenges affect the integration of sustainability and 4IR skills in mathematics teaching?
4. How do community partnerships support or hinder the advancement of sustainability-oriented mathematics education?

By explicitly addressing these questions, this study aims to inform strategies that bridge the gap between national policy aspirations and classroom realities, ensuring that mathematics education equips learners with the skills needed for participation in the digital economy and for contributing to sustainable innovation.

2. Literature Review

This section summarises the relevant literature from global, national, and community-based perspectives.

2.1 Mathematics Education and Sustainable Development: A Global Perspective

Mathematics education is increasingly recognised as a key driver in equipping learners with the skills to address global challenges, particularly through its alignment with Sustainable Development Goal 4 on inclusive and equitable education (UNESCO, 2020). Sustainability education theory underscores the importance of systems thinking, critical reflection, and action competence, positioning mathematics as a tool for linking abstract concepts to socio-environmental issues (Andersson, Augustine, & Gambarato, 2025).

Empirical studies further show that embedding sustainability contexts such as climate modelling, poverty analysis, and resource distribution can enhance both conceptual understanding and civic engagement (González-Gómez & Jeong, 2022; Vásquez et al., 2023). While international cases, including Finland, Brazil, and India, illustrate success through project-based, sustainability-oriented mathematics, South Africa faces challenges in this area. Although the CAPS policy integrates cross-cutting themes like environmental responsibility, these remain marginalised in under-resourced schools (Department of Basic Education [DBE], 2011). Furthermore, limited empirical evidence exists on how teachers implement sustainability principles in rural mathematics classrooms, highlighting the need for context-sensitive models grounded in sustainability education theory to drive socio-economic transformation.

2.2 Mathematics Education in the Age of the Fourth Industrial Revolution
The Fourth Industrial Revolution (4IR) underscores the economic value of advanced skills, aligning with Human Capital Theory, which views education as an investment that drives innovation and growth (Becker, 1994). Mathematics, which is foundational to AI, robotics, and big data, is central to preparing learners for digital economies (Hossain, 2023). Countries such as South Korea, Singapore, Germany, and Australia have restructured curricula to include coding, algorithmic thinking, and simulations, directly enhancing innovation capacity (Khalil, 2022).

In South Africa, however, the integration of 4IR skills remains uneven. Despite supportive policies like the 2019 White Paper on Science, Technology and Innovation, limited teacher training, inadequate resources, and curriculum rigidity hinder implementation, especially in rural schools (Department of Science & Innovation, 2019; Naidoo & Israel, 2021; Kaziya, 2025). Consequently, key competencies such as data interpretation and modelling remain underdeveloped, leaving many learners ill-prepared for a digital economy and reinforcing existing inequalities (Farooq, 2024).

2.3 Integrating Sustainable Development and 4IR in Mathematics Education
The convergence of sustainable development and the Fourth Industrial Revolution (4IR) call for reimagining mathematics education as a driver of both technological competence and socio-ecological awareness (Mncwango, 2023). International examples show how countries like Sweden, Japan, and the Netherlands use climate-related big data, virtual labs, and sustainability-focused problem-solving, although such innovations rely on strong infrastructure and adaptable curricula (Roellke, 2024; Mdodoana-Zide & Chimbi, 2025).

In South Africa, especially in rural areas, integration is hindered by poor internet, outdated technology, and limited teacher preparation in sustainability and digital skills (Sithole & Mbukanma, 2025). Still, community-led projects demonstrate potential through mobile apps and digital mapping for local challenges like water access. Meaningful integration requires systemic curriculum reform, targeted teacher development, infrastructure investment, and culturally relevant resources (Verawati & Nasrina, 2025). While global models provide inspiration, South African solutions must remain contextually grounded to advance sustainability and digital inclusion (Agbat et al., 2024).

2.4 Integrating Sustainable Development and 4IR in Mathematics Education
The convergence of sustainability and the Fourth Industrial Revolution (4IR) call for mathematics education that is both technologically advanced and socially

responsive. The TPACK framework (Mishra & Koehler, 2006) underscores the need for teachers to integrate content knowledge, pedagogy, and digital tools for meaningful learning. International examples, such as climate data projects in Sweden and renewable energy simulations in the Netherlands, show how digital innovation can embed sustainability in mathematics.

In South Africa, however, integration is constrained by poor connectivity, limited teacher training, and a rigid curriculum, particularly in rural areas. While NGOs and universities have begun introducing mobile apps and GIS projects, systemic reforms, curriculum redesign, teacher professional development, and infrastructure investment, are essential to ensure that mathematics education promotes both sustainability and digital inclusion.

3. Theoretical Framework

This study is guided by an **integrated theoretical framework** that combines Constructivist Theory (Piaget, 1970), Social Constructivism (Vygotsky, 1978), Human Capital Theory (Becker, 1994), Sustainability Education Theory (Sterling, 2019; UNESCO, 2020), and the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006). Together, these theories offer a holistic perspective for reimagining mathematics education in South African secondary schools, ensuring that it is learner-centred, socio-economically relevant, sustainability-driven, and technologically responsive to the demands of the Fourth Industrial Revolution (4IR).

Constructivist Theory emphasises developmental readiness, experiential learning, and reflective thinking, highlighting how learners individually construct mathematical knowledge. Social Constructivism complements this by focusing on collaboration, scaffolding, and the Zone of Proximal Development, situating mathematics learning within social, cultural, and linguistic contexts. These two lenses jointly foreground learner-centred pedagogies that promote critical thinking, problem-solving, and adaptability—skills that are central to 4IR and sustainability education.

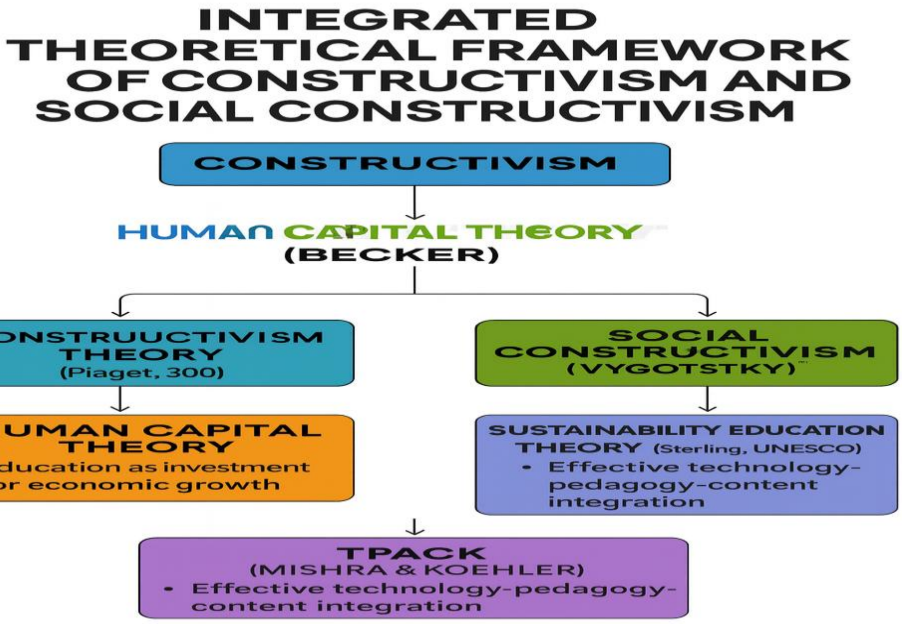

Figure 1: Integrated Theoretical Framework for Mathematics Education in the Fourth Industrial Revolution

The framework combines Constructivism (blue), Social Constructivism (green), Human Capital Theory (orange), Sustainability Education Theory (teal), and TPACK (purple) to provide a comprehensive foundation for understanding how mathematics education can support sustainable development and prepare learners for the demands of 4IR.

By integrating multiple theories, the framework positions mathematics education as both a cognitive and social process that builds human capital, advances sustainability, and leverages technology for innovation. Human Capital Theory frames mathematics as an investment in skills for national development and economic competitiveness, while Sustainability Education Theory situates learning within socio-environmental challenges, fostering systems thinking and action competence. The TPACK framework adds a practical dimension by showing how content, pedagogy, and technology can be combined, particularly through tools like coding platforms and simulations, to bridge resource gaps, enhance collaboration, and make mathematics more relevant in rural classrooms.

4. Research Methodology

4.1 Research Design

This study employed a Research and Development (R&D) design framed within the interpretivist paradigm. The interpretivist orientation was suitable because it prioritises understanding the lived experiences, meanings, and interpretations of participants in their socio-cultural contexts (Paudel, 2024; Tisdell & Meriam, 2025). An R&D design was chosen as it not only facilitated the generation of rich, qualitative insights but also supported the iterative development of practical recommendations for integrating sustainability and Fourth Industrial Revolution (4IR) competencies into mathematics education. The approach allowed for cycles of exploration, design, and refinement, thereby linking theoretical understanding with practice-oriented outcomes. The data collection involved qualitative methods such as interviews, focus group discussions, and classroom observations to capture the teachers' and learners' experiences of sustainability and digital integration in mathematics. These insights were then used to inform contextually relevant strategies and recommendations, making the R&D design particularly appropriate for the study's developmental aims (Creswell & Poth, 2016).

4.2 Population and Sampling

The study targeted Grade 10 mathematics teachers and learners from the rural secondary schools of the OR Tambo District. A purposive sample of 20 participants (15 teachers and 5 learners) from five schools was selected to ensure direct relevance to the study's R&D design (Campbell et al., 2020). Teachers were chosen for their active classroom roles, while learners were selected for their involvement in projects linking mathematics to sustainability. The sample was comprised of 12 females and 8 males, with learners aged 15–17, providing diverse perspectives to inform the recommendations on integrating sustainability and 4IR competencies into mathematics education.

4.3 Data Collection Instruments and Procedures

The data was generated from both teachers and learners using multiple instruments to facilitate methodological triangulation (Flick, 2018):

- Teachers and Learners: Semi-structured interviews with teachers and focus group discussions (FGDs) with learners were conducted using open-ended guides aligned with the research objectives. The guides explored four key areas: (1) perceptions of integrating sustainability and technology in mathematics, (2) pedagogical strategies, (3) challenges encountered, and (4) lived experiences and reflections. This ensured consistency while allowing the participants to provide rich insights.
- Learners: FGDs further encouraged peer interaction and reflection on shared experiences, offering a deeper insight into how learners perceived and engaged with sustainability-related mathematics activities while capturing group dynamics and shared understandings.
- Both Groups: Non-participant classroom observations captured actual teaching and learning practices. A context-adapted observation schedule guided the data collection on instructional strategies, learner participation, technology use, contextual problem-solving, and collaboration. Adaptations allowed the inclusion of both advanced digital tools and low-tech resources, ensuring systematic and context-sensitive recording.
- The field notes documented contextual details, non-verbal cues, and environmental factors that might have influenced teaching and learning.

The data collection was conducted over six weeks with the site visits to each school scheduled to ensure equal observation opportunities across all cases.

4.4 Measures of Quality Control

Credibility was enhanced through member checking where the participants reviewed summaries of their interview or FGD transcripts to verify accuracy and authenticity (Birt et al., 2016). Dependability was ensured by maintaining a clear audit trail of all research activities, including interview guides and coding frameworks. Transferability was addressed through detailed descriptions of the research context, participants, and procedures, enabling readers to assess the applicability of the findings to similar settings.

4.5 Data Analysis
The data was analysed using Braun and Clarke's (2019) six-step thematic analysis: familiarising with transcripts, generating initial codes, grouping codes into themes, reviewing and refining themes, defining and naming them, and finally producing the report with illustrative participant quotes.
The themes were refined iteratively to ensure conceptual clarity and alignment with the study's objectives. This process identified both shared and divergent experiences across cases, offering nuanced insights into the integration of sustainability and technology in rural mathematics classrooms.

4.6 Ethical Considerations
Ethical clearance was obtained from the Faculty Research and Higher Degrees Committee (FRHDC) at Walter Sisulu University. Permission to conduct the study was also granted by the Eastern Cape Department of Basic Education. All participants provided informed consent, with parental consent obtained for learners under 18. Anonymity was maintained using pseudonyms, and all data was stored securely on password-protected devices. Participation was voluntary, and the participants could withdraw at any stage without penalty.

5. Findings and Discussion
Several themes emerged from the data generated for this study. The diagram below presents a graphical presentation of the themes. The findings highlighted the four interconnected dimensions crucial for advancing sustainable development in mathematics education within the Fourth Industrial Revolution (4IR): understanding sustainable development and 4IR, teacher preparedness, technology integration, and community collaboration. Together, these emphasised that sustainability in mathematics education requires curriculum alignment, teacher capacity building, adequate infrastructure, and active community engagement.

Sustainable Development in Mathematics

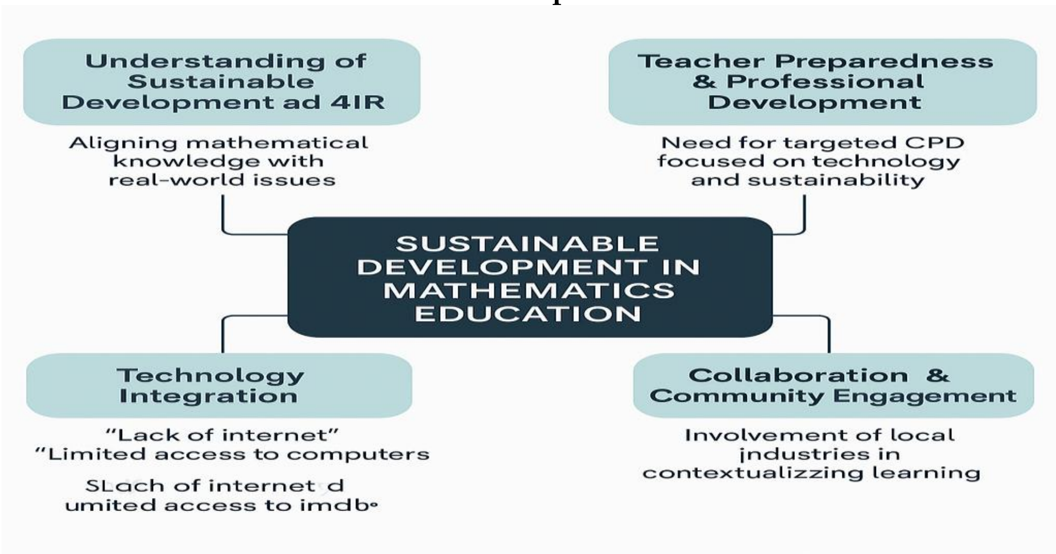

Figure 3: Themes demonstrating sustainable development in Mathematics

Figure 3: Key findings on sustainable development in mathematics education showing the interconnected roles of conceptual understanding, teacher professional growth, technological access, and community collaboration in fostering relevant and impactful learning experiences.

The findings emphasised that a holistic approach is necessary for sustainable mathematics education, one that integrates contextualised content, continuous professional development, equitable access to digital resources, and strategic partnerships with local industries. Addressing these dimensions collectively equips learners with the competencies, critical thinking skills, and adaptive capacities needed to thrive in the Fourth Industrial Revolution (4IR) while contributing to sustainable development goals.

5.1. Understanding of Sustainable Development and 4IR

Teachers viewed sustainable development in mathematics as aligning mathematical knowledge with real-world problems such as environmental management and social equity. One teacher remarked, *"I see sustainable development as using mathematics to address real-world challenges, like how to allocate resources fairly or measure the impact of certain actions on the environment."* Another added, *"When we discuss sustainability in the classroom, it is about showing learners that math is not just numbers, but a tool for making decisions that affect the world they live in."*

5.2. Technology Integration

Teachers recognised the value of digital tools but cited barriers such as poor connectivity, limited devices, and inadequate training. One participant explained, *"I try to use online resources and interactive whiteboards, but the lack of reliable internet makes it difficult to maintain consistency."* Another added, *"We would benefit greatly from more training and better equipment. The interest is there, but the tools are not."*

5.3. Teacher Preparedness and Professional Development

Teachers consistently highlighted the absence of structured government-led professional development (CPD). One teacher stated, *"I have attended a few workshops organised by non-profits, and they have been invaluable, but I wish there were more systematic training opportunities from the government."* Another reflected, *"Without proper training, it is hard to fully incorporate sustainability concepts into the curriculum, especially when we are still learning to use the technology ourselves*."

5.4. Student Engagement and Learning Outcomes

Teachers observed that project-based learning and technology-supported assessments improved student engagement. One noted, "*When we worked on a project to calculate the school's water usage and how to reduce it, the learners were very enthusiastic. They saw the relevance of math in their daily lives*." Another explained, "*Using technology to create interactive quizzes and simulations kept the students more engaged than traditional methods. They were more motivated to participate and explore*."

5.5. Collaboration and Community Engagement

Teachers highlighted the benefits of community partnerships with industries and NGOs. One participant shared, "*We have collaborated with local farmers to show students how math can help manage crop yields and predict market trends*." Another added, "*When students see how their calculations and models can impact the community, they take pride in their work* ***and understand the value of mathematics beyond the classroom.***"

5.6. Learners' Perspectives

Learners demonstrated a limited understanding of sustainability and 4IR concepts, often perceiving them as abstract or disconnected from their education. One learner said, "*Our maths lessons do not show us how the subject can solve real-world problems like climate change or unemployment*." Another noted, "*We always hear about sustainability and the Fourth Industrial Revolution, but no one has explained what it means for us as learners*."

Regarding technology, frustrations were common: "*Most of the time, we cannot even use the computer lab because it is either locked, or the internet is down*." Another learner added, "*The tablets we got are broken or not charged, so we return to chalk and talk.*" A third explained, "*We are told to use apps, but no one shows us how. We do not even have proper login details sometimes*."

Learners also commented on engagement: "*Lessons feel repetitive and boring, with too much copying and not enough problem-solving*." Another observed, "*We hardly do group work, and our parents don't really know what we are learning*."

6. Discussion of findings

The findings revealed a tension between the teachers' enthusiasm for sustainability and technology integration and the learners' limited engagement with these concepts in practice. Teachers articulated mathematics as a tool for addressing real-world problems, such as resource allocation and environmental management, emphasising that *"math is not just numbers, but a tool for making decisions that affect the world they live in."* This aligns with Education for Sustainable

Development (UNESCO, 2020), which positions mathematics as central to developing critical citizenship and problem-solving competencies. However, learners described sustainability and 4IR as abstract, noting that *"No one has explained what it means for us as learners."* This contradiction highlights a gap between curricular intentions and classroom realities where policy discourses have not yet been translated into learner-centred pedagogy.

Technology integration presented a similar paradox. Teachers recognised the pedagogical value of digital tools, with one stating, *"The interest is there, but the tools are not."* Learners expressed frustration at locked computer labs, broken devices, and the superficial use of tablets: *"We are told to use apps, but no one shows us how."* These experiences resonated with the Technology Acceptance Model (Davis, 1989), where perceived usefulness is high, but ease of use remains constrained by infrastructural barriers. This also supports broader critiques that technology in under-resourced contexts often reinforces traditional methods rather than transforming learning (UNESCO, 2021).

Professional development emerged as a critical enabler yet remains underdeveloped. Teachers' reliance on NGO workshops underscores the systemic gaps in government-led CPD. As one teacher explained, *"Without proper training, it is hard to fully incorporate sustainability concepts into the curriculum."* This finding was consistent with the TPACK framework (Mishra & Koehler, 2006), which highlighted the importance of integrating pedagogy, content, and technology with transformative learning theory (Mezirow, 1997), which calls for reflective practice. The lack of structured CPD constrains the teachers' ability to embed 21st-century skills and sustainability principles into mathematics teaching.

Finally, community partnerships offered a promising pathway for contextualised learning. Teachers described collaborations with farmers to model crop yields, while learners expressed pride in seeing their work applied in local contexts. Such practices reflected ecological systems theory (Bronfenbrenner, 1979) and critical mathematics education, both of which position learning as socially situated and empowering. Yet the lack of parental involvement and minimal group work reported by learners suggested that community collaboration remains sporadic rather than systemic.

7. Conclusion

This study examined the integration of sustainable development principles and Fourth Industrial Revolution (4IR) competencies into mathematics education within selected South African schools, with a focus on rural contexts. The findings revealed a complex and uneven landscape. While there was evidence of teacher enthusiasm for incorporating sustainability themes and digital tools into mathematics instruction, such an integration was constrained by systemic barriers, including inadequate infrastructure, unequal access to technology, insufficient teacher preparation in digital pedagogy, and the limited presence of sustainability concepts in actual curriculum delivery. These challenges, widely noted in both South African and international studies, emphasise that the mere presence of technology does not automatically translate into pedagogical transformation or improved learner outcomes.

Importantly, this study does not claim a direct causal link between the use of 4IR technologies and measurable improvements in sustainable mathematics education outcomes. Rather, the evidence suggests that technology integration must be situated within broader systemic reform that includes curriculum realignment, targeted teacher professional development, equitable resourcing, and community engagement. Without addressing these foundational issues, technology risks becoming an underutilised asset rather than a catalyst for transformative learning.

The conclusion calls for a balanced and contextually informed approach: acknowledging the progress made in awareness and policy discourse while critically recognising the persistent socio-economic and institutional challenges that limit meaningful integration. Sustainable mathematics education in the 4IR era can only be realised through coordinated, multi-stakeholder action that aligns teacher capacity, curriculum content, infrastructure investment, and community partnerships within a coherent policy framework.

8. Recommendations and Practical Implications

Considering the findings and their limitations, the following recommendations are proposed to guide practice, policy, and further research:

The study highlights several areas that require attention to align mathematics education with sustainability goals and the demands of the Fourth Industrial Revolution (4IR). Continuous, contextually relevant professional development programmes should be prioritised, enabling teachers to integrate sustainability principles with digital pedagogy. These initiatives need to move beyond one-off workshops toward sustained models of support, such as peer learning networks, structured mentoring, and partnerships with higher education institutions.

At the same time, equitable investment in digital infrastructure is essential. Reliable ICT resources, including computers, internet connectivity, and interactive platforms, should be made available particularly in rural and underserved schools. Attention must also be given to school-wide policies that ensure the purposeful use of facilities, as well as funding allocations that cover both procurement and ongoing maintenance. Curriculum reform is equally critical, with syllabi revised to embed sustainability principles and 4IR competencies through locally relevant, real-world applications. Age-appropriate modules should incorporate mathematical modelling, data literacy, and problem-solving for sustainability challenges. Integration should cut across subjects to foster interdisciplinary learning and holistic understanding.

Strengthening community and industry partnerships can further bridge the gap between classroom learning and real-world contexts. Collaborations with industries, cooperatives, NGOs, and environmental agencies can expose learners to authentic projects, mentorship opportunities, and resources that cultivate mathematical understanding alongside civic and environmental responsibility. Finally, systemic support is needed through policy alignment. National and provincial frameworks should explicitly reflect the priorities of sustainability and 4IR readiness in teacher training mandates, curriculum guidelines, and funding strategies.

Monitoring mechanisms must assess not only the access to resources but also their pedagogical use and impact. Embedding digital and futures literacy across core subjects will further prepare learners for active citizenship and economic participation. Teacher development should include practical, hands-on training that builds confidence in applying digital strategies, from basic multimedia to advanced e-learning, ensuring that educators are equipped for technology-enhanced, learner-centred teaching.

Final Implication: The integration of sustainability and Fourth Industrial Revolution (4IR) competencies into mathematics education extends beyond the adoption of digital tools. It requires a comprehensive reform agenda that aligns the structural, pedagogical, and socio-economic dimensions of the education system. This includes investment in infrastructure, reliable connectivity, and supportive policy frameworks alongside a redesign of the curriculum that embeds real-world applications. Continuous professional development is also essential to equip teachers with the skills to integrate sustainability and digital pedagogy, while addressing inequalities that limit access, especially in rural and underserved schools.

This vision in South Africa calls for collaborative efforts from the government, educators, communities, and the private sector. Policy coherence, systemic support, and sustained teacher mentoring are critical, while partnerships with industries and communities can provide authentic learning contexts. By treating this integration as a long-term transformation rather than a quick technological fix, education systems can prepare learners with the critical thinking, problem-solving, and adaptive skills needed for sustainable development and global competitiveness in the 4IR era.

9. Limitations and Future Research

While this study offers important insights into the integration of sustainable development and Fourth Industrial Revolution (4IR) competencies in mathematics education, several limitations must be noted. The qualitative multiple-case study design, with a small purposive sample of 15 teachers and 5 learners, limits generalisability beyond the rural schools studied.

The research explored perceptions and practices rather than establishing causal links between technology use and learning outcomes, so the findings should be interpreted cautiously. Resource disparities across schools, such as ICT access, teacher training, and community engagement, also influenced the extent of integration. Finally, the reliance on self-reported data may involve social desirability bias and classroom observations which, although useful for triangulation, were limited in scope and duration.

Future research should adopt mixed methods approaches that combine qualitative insights with quantitative measures to better assess the impact of sustainability and technology integration in mathematics education. Longitudinal studies could track how interventions like professional development and infrastructure investment influence teaching and learning over time. Comparative studies between rural and urban schools, or across provinces, would highlight the role of context, while research on learner-led sustainability projects could reveal how agency and community engagement support both educational and societal goals.

Conflict of Interest

The author confirms that there are no known financial, personal, or professional conflicts of interest that could have appeared to influence the work reported in this manuscript.

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10. References

Agbata, B. C., Obeng-Denteh, W., Abraham, S., Asante-Mensa, F., Kwabi, P. A., Okpako, S. O., ... & Arivi, S. S. (2024). Advancing mathematics education in Africa: Challenges, strategies, and prospects. *Science World Journal, 19*(3), 808–818. https://doi.org/10.4314/swj.v19i3.28.

Ampo, W. M., Rullen, M. S. M., Deguit, E. O., Perocho, R. V., & Romero, P. J. B. (2025). From Traditional School to Virtual Classroom: Students' Lived Experiences on Blended Learning Implementation. *International Journal of Education and Emerging Practices*, *1*(2), 1-15. http://injeep.org/index.php/injeep/article/view/21.

Andersson, P., Augustine, L. and Rampazzo Gambarato, R., 2025. Advancing Social Sustainability Through the Development of Action Competence: A Scoping Literature Review. *Sustainability*, *17*(8), p.3661.

Alwaqdani, M. (2025). Investigating teachers' perceptions of artificial intelligence tools in education: potential and difficulties. *Education and Information Technologies*, *30*(3), 2737-2755.

Bachmann, N., Tripathi, S., Brunner, M., & Jodlbauer, H. (2022). The contribution of data-driven technologies in achieving the Sustainable Development Goals. *Sustainability*, *14*(5), 2497. https://doi.org/10.3390/su14052497.

Becker, G. S. (1994). Human capital revisited. In *Human Capital: A Theoretical and Empirical Analysis with Special Reference to Education, third edition* (pp. 15–28). The University of Chicago Press.

Blose, P. (2025). Pedagogical Approaches for Teaching Education for Sustainable Development in the Technology Education Curriculum. *Research in Social Sciences and Technology*, *10*(1), 209–232. https://doi.org/10.46303/ressat.2025.12.

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: a tool to enhance trustworthiness or merely a nod to validation? *Qualitative health research*, *26*(13), 1802-1811.

Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative research in sport, exercise and health*, *11*(4), 589–597.

Bronfenbrenner, U. (1979). *The ecology of human development: Experiments by nature and design*. Harvard University Press.

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., ... & Walker, K. (2020). Purposive sampling: complex or simple? Research case examples. *Journal of Research in Nursing*, *25*(8), 652–661. https://doi.org/10.1177/1744987120927206.

Chigona, A. (2020). Digital inclusion in South African schools: Rethinking technology access in disadvantaged contexts. *South African Journal of Education, 40*(2), 1–10. https://doi.org/10.15700/saje.v40n2a1725.

Choudhary, H., & Bansal, N. (2022). Barriers affecting the effectiveness of digital literacy training programs (DLTPs) for marginalised populations: a systematic literature review. *Journal of Technical Education and Training*, *14*(1), 110–127. https://doi.org/10.30880/jtet.2022.14.01.010.

Cirneanu, A. L., & Moldoveanu, C. E. (2024). Use of digital technology in integrated mathematics education. *Applied System Innovation*, *7*(4), 66. https://doi.org/10.3390/asi7040066.

Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage Publications.

Darbellay, F. (2024). When interdisciplinarity meets creativity: exploring interdisciplinary creative teaching in the 21st century. In Handbook of Interdisciplinary Teaching and Administration (pp. 317–339). Edward Elgar Publishing. https://doi.org/10.4337/9781035309870.00029.

Davis, F.D., 1989. Technology acceptance model: TAM. *Al-Suqri, MN, Al-Aufi, AS: Information Seeking Behaviour and Technology Adoption*, *205*(219), p.5.

Department of Basic Education (DBE). (2011). *Curriculum and Assessment Policy Statement (CAPS): Grades 10–12 Mathematics*. Pretoria: Department of Basic Education.

Department of Basic Education. (2019). *White Paper on Science, Technology and Innovation*. Pretoria: Government of South Africa.

Department of Basic Education. (2020). *Curriculum and Assessment Policy Statement (CAPS): Mathematics*. Pretoria: Department of Basic Education.

Department of Basic Education (DBE). (2024) *Curriculum review: strengthening alignment with the Fourth Industrial Revolution*. Pretoria: Department of Basic Education.

Department of Science and Innovation. (2019). White paper on science, technology and innovation. Pretoria: Department of Science and Innovation.

Farooq, N. (2024). Cross-Disciplinary Collaboration in Higher Education: Preparing Students for a Complex World. *Frontiers in Interdisciplinary Educational Methodology*, *1*(03), 127-136. https://fiem.com.pk/index.php/Journal/article/view/18.

Flick, U. (2018). Doing qualitative data collection–charting the routes. *The SAGE handbook of qualitative data collection*, 1-16. https://www.torrossa.com/en/resources/an/5018779#page=32.

González-Gómez, D., Jeong, J. S., & Cañada-Cañada, F. (2022). Enhancing science self-efficacy and attitudes of Pre-Service Teachers (PST) through a flipped classroom learning environment. *Interactive Learning Environments*, *30*(5), 896–907. https://doi.org/10.1080/10494820.2019.1696843.

Hossain, K. A. (2023). Analysis of present and future use of artificial intelligence (AI) aligns with the fourth industrial revolution (4IR). *Scientific Research Journal*, *11*, 1-50. http://dx.doi.org/10.31364/SCIRJ/v11.i8.2023.P0823954.

Khalil, R. Y. (2022). The Impact of STEM-Based Curriculum on the Development of Creative Thinking of High School Students in the United Arab Emirates.

Kaziya, K. (2025). A Systematic Review of Technology Integration in Mathematics Education: Perspectives from Rural Zambia in Kalomo District. https://doi.org/10.21203/rs.3.rs-6374363/v1.

Mdodana-Zide, L., & Chimbi, G. T. (2025, July). Transforming education in a rural ecosystem: school libraries as hubs for teaching-learning innovation. In *Frontiers in Education* (*10*, p. 1601206). Frontiers Media SA. https://doi.org/10.3389/feduc.2025.1601206.

Mezirow, J., 1997. Transformation theory out of context. *Adult education quarterly*, *48*(1), pp.60-62.

Mncwango, A. (2023). Leading education for sustainable livelihoods in a 4IR-driven economy: A case study evaluating the Partners for Possibilities leadership model. University of Johannesburg (South Africa).

Mhlanga, D. (2023). ChatGPT in education: Exploring opportunities for emerging economies to improve education with ChatGPT. *Available at SSRN 4355758*.

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A framework for teacher knowledge. *Teachers College Record, 108*(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x.

Motseki, P., & Sophy, K. (2024). Mathematics Teachers in the Twenty-First Century—What Affordances and Constraints Lie in Preparing Teachers for the Fourth Industrial Revolution (4IR) in South Africa. In *Mathematics Teacher Training and Development in Africa: Trends at Primary and Secondary School Levels* (pp. 193–209). Cham: Springer Nature Switzerland. https://link.springer.com/chapter/10.1007/978-3-031-68755-6_10.

Mughal, M. M. B. B. (2025). Effects of Artificial Intelligence on Secondary and Higher Secondary Students (Grades 9–12) in District Khairpur Mirs: https://doi. org/10.5281/zenodo. 16942380. *ASSAJ*, *4*(01), 3009-3027.

Naidoo, G. M., & Israel, C. (2021). A critique of online learning in higher education during the coronavirus lockdown level 5 in South Africa. *African Journal of Development Studies*, *11*(1), 127.

Organisation for Economic Co-operation and Development (OECD). (2020). *Teaching and Learning International Survey (TALIS) 2018 Results: Teachers and School Leaders as Valued Professionals*. OECD Publishing. https://doi.org/10.1787/19cf08df-en.

Okello, J. and Nsubuga, E.T., 2025. Leadership Influence and Behavioural Practices in Small and Medium Enterprises in Uganda's Greater Kibaale Region. *Global Journal of Research in Management and Social Sciences*, *1*(1), pp.12–27.

Paudel, P. (2024). Examining paradigmatic shifts: Unveiling the philosophical foundations shaping social research methodologies. *Journal of the University of Ruhuna*, *12*(1).

Piaget, J., & Duckworth, E. (1970). Genetic epistemology. *American Behavioural Scientist*, *13*(3), 459–480.

Rico, A., Agirre-Basurko, E., Ruiz-González, A., Palacios-Agundez, I., & Zuazagoitia, D. (2021). Integrating mathematics and science teaching in the context of education for sustainable development: Design and pilot implementation of a teaching-learning sequence about air quality with pre-service primary teachers. *Sustainability*, *13*(8), 4500. https://doi.org/10.3390/su13084500.

Roellke, J. Q. G. (2024). Climate clash: navigating the dilemma between carbon-intensive study abroad and climate action. *Master Thesis Series in Environmental Studies and Sustainability Science*.

Serrano, D. R., Dea-Ayuela, M. A., Gonzalez-Burgos, E., Serrano-Gil, A., & Lalatsa, A. (2019). Technology-enhanced learning in higher education: How to enhance student engagement through blended learning. *European Journal of Education*, *54*(2), 273–286. https://doi.org/10.1111/ejed.12330.

Sithole, V. L., & Mbukanma, I. (2024). Prospects and Challenges to ICT Adoption in Teaching and Learning at Rural South African Universities: A Systematic Review. *Research in Social Sciences and Technology*, *9*(3), 178-193.

Sterling, S. (2019). Sustainability Education Theory. In S. Sterling (Ed.), *Sustainability Education: Perspectives and Practice across Higher Education* (pp. 245–291). Routledge.

Sujatha, S., & Vinayakan, K. (2023). Integrating Math and Real-World Applications: A Review of Practical Approaches to Teaching. *International Journal of Computational Research and Development*, *8*(2), 55–60.

Tisdell, E. J., Merriam, S. B., & Stuckey-Peyrot, H. L. (2025). *Qualitative research: A guide to design and implementation*. John Wiley & Sons.

Tiwary, R., & Sharma, V. (2025). EQUATIONS FOR EARTH: THE ROLE OF MATHEMATICAL MODELING IN ACHIEVING SUSTAINABILITY GOALS. *Int. J. of Electronics Engineering and Applications*, *13*(1). https://ijeea.in/wp-content/uploads/130105-Dr.-Rekha.pdf.

UNESCO. (2020). *Education in a Post-COVID World: Nine Ideas for Public Action*. International Commission on the Futures of Education. https://unesdoc.unesco.org/ark:/48223/pf0000373717

UNESCO. (2021). *Reimagining our futures together: A new social contract for education*. https://unesdoc.unesco.org/ark:/48223/pf0000379707.

Verawati, N. N. S. P., & Nisrina, N. (2025). Reimagining physics education: addressing student engagement, curriculum reform, and technology integration for learning. *International Journal of Ethnoscience and Technology in Education*, *2*(1), 158–181. https://doi.org/10.33394/ijete.v2i1.14058.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Yadav, R. (2022). *The role of digital technologies in transforming mathematics education: Insights from higher education instructors in South Africa*. African Journal of Research in Mathematics, Science and Technology Education, *26*(1), 14–28. https://doi.org/10.1080/18117295.2022.2020634,

Yin, R. K. (2018). *Case study research and applications* (6). Thousand Oaks, CA: Sage.