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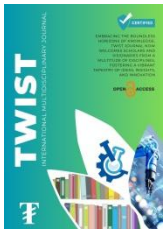

Bridging the Digital Divide: Integrating Fourth Industrial Revolution (4IR) Technologies in TVET for Enhanced Youth Skilling and Employability in South Africa

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Abstract
The rapid advancement of Fourth Industrial Revolution (4IR) technologies is reshaping global labour markets, necessitating a paradigm shift in Technical and Vocational Education and Training (TVET) to equip youth with future-ready skills. This position paper critically examines the integration of 4IR technologies in South African TVET colleges, arguing that a systemic and policy-driven approach is required to bridge the digital divide and enhance youth employability. This paper synthesises existing research on 4IR adoption in TVET using a systemic literature review, exploring the challenges, opportunities, and policy imperatives for effective implementation. The findings highlight persistent infrastructural disparities, limited digital literacy among lecturers and students, and misalignment between industry demands and curriculum offerings. The paper advocates for strategic investments in digital infrastructure, capacity-building for TVET lectures, and stronger industry-TVET collaborations to ensure inclusive and sustainable skilling pathways. By positioning 4IR technologies as a catalyst for skills development and economic mobility, this paper contributes to the discourse on advancing TVET for the digitalised world, particularly in the Global South.

Keywords
Fourth industrial revolution, TVET, Youth skilling, Employability, Digital divide, Systemic literature review, South Africa

INTRODUCTION

The Fourth Industrial Revolution (4IR) is characterised by a convergence of digital, biological, and physical technologies transforming industries, economies, and societies globally (Hossain, 2023; Makazhe & Maramura, 2023; Moll, 2022; Voronkova et al., 2023). Unlike previous industrial revolutions, which were driven by mechanisation, electrification, and computerisation, 4IR is defined by automation, artificial intelligence (AI), the Internet of Things (IoT), blockchain, robotics, and big data analytics (Voronkova et al., 2023). These technologies are reconfiguring traditional industries and creating new economic sectors, redefining the nature of work and employability.

Global labour markets are undergoing rapid digital transformation, with industries increasingly requiring workers adept in digital literacy, computational thinking, and problem-solving (Challoumis, 2024). As a result, there is a growing emphasis on skilling, reskilling, and upskilling to ensure that individuals remain competitive in the job market. Traditional job roles are becoming obsolete, and emerging occupations demand higher-order cognitive, technical, and socio-emotional skills (Sharef et al., 2024). Despite the promise of 4IR, the digitalisation of work also exacerbates labour

market inequalities. Developing economies, such as South Africa, face structural challenges such as limited access to digital infrastructure, inadequate lecturer training, and curriculum misalignment with industry demands (Ferreira-Meyers, 2024; Kruger & Rosslyn-Smith, 2024). This digital divide—defined as the gap between those with access to digital technologies and those without—poses a significant threat to inclusive economic growth and social mobility (Potter & Stilinski, 2024).

Importance of TVET in Preparing Youth for Digitalised Workplaces

Technical and Vocational Education and Training (TVET) equips youth with practical, job-relevant skills that enhance employability. Unlike traditional academic pathways, TVET focuses on skills-based education, ensuring that graduates are work-ready and capable of meeting the demands of evolving industries (Stanford, 2024; Suryati et al., 2024). In the context of 4IR, TVET colleges must adapt their curricula and pedagogical approaches to incorporate digital skills, AI literacy, automation, and emerging technologies (Kivindu, 2024). This requires a shift from conventional vocational training—which often emphasises manual and technical trades—to digitally integrated learning models that prepare students for the future of work(Kana & Letaba, 2024). Magagula and Awodiji (2024) noted that South Africa's TVET sector is a key driver for youth skilling and economic development, particularly in addressing youth unemployment and skills mismatches. The integration of 4IR technologies in TVET remains uneven. Some institutions have made strides in incorporating digital tools, while others struggle due to resource constraints, policy gaps, and a lack of industry collaboration (Sutherland, 2020). Several recent studies highlighted that since many young people from disadvantaged backgrounds rely on TVET for career development, ensuring that TVET colleges can effectively prepare students for digitalised workplaces is imperative(Leeuw; Mabunda & Frick, 2020; Mthabela, 2024; Nkambule & Ngubane, 2023; Zenda & Ramatsetse, 2024; Zeng). Without strategic interventions, South Africa risks widening existing socio-economic inequalities, as those without access to digital skills will be left behind in the evolving labour market(Mokofe, 2024).

Addressing the Digital Divide and Aligning TVET with 4IR Demands

Despite recognising 4IR's transformative potential, there is a critical gap in research and policy on how TVET colleges in South Africa can effectively integrate digital technologies to prepare youth for technology-driven employment sectors(Pila et al., 2024). The digital divide remains a barrier to the successful adoption of 4IR in TVET, disproportionately affecting historically disadvantaged institutions and rural communities(Mututwa, 2024). Based on the above exposition, this position paper aims to critically examine the integration of 4IR in South African TVET colleges using a systemic literature review, specifically focusing on:

i. Identifying systemic barriers to 4IR adoption in TVET.
ii. Synthesising existing research through a systemic literature review.
iii. Proposing policy recommendations for sustainable and inclusive 4IR integration in TVET.

CONCEPTUAL AND THEORETICAL FRAMEWORK

In this section, we define key concepts relevant to the study and outline theoretical perspectives that underpin the analysis of 4IR integration in TVET.

Definition of Key Concepts

Fourth Industrial Revolution (4IR)

The 4IR refers to the current era of technological advancement, marked by the convergence of digital, biological, and physical systems (Hossain, 2023). David et al. (2024) asset that unlike previous industrial revolutions, which introduced mechanisation, electrification, and digitisation, 4IR is characterised by artificial intelligence (AI), automation, robotics, the Internet of Things (IoT), blockchain, 3D printing, and cloud computing. These technologies are reshaping industries, altering job roles, and demanding new skill sets from the workforce (Ngomana, 2023). For TVET colleges, 4IR represents both a challenge and an opportunity. On the one hand, skills gaps and infrastructure limitations hinder the ability of TVET colleges to integrate advanced digital learning technologies (Mthabela, 2024). On the other hand, adopting 4IR-aligned curricula could enhance youth employability, economic participation, and innovation capacity in South Africa (Maringe et al., 2022).

Technical and Vocational Education and Training (TVET)

Technical and Vocational Education and Training (TVET) refers to educational programmes and training initiatives designed to equip individuals with practical skills, technical knowledge, and industry-specific competencies to enhance their employability(Kebede et al., 2024; Meunmany, 2024; Varma & Malik, 2023). TVET colleges are crucial in bridging the gap between education and the labour market, especially in economies with high youth unemployment rates like South Africa(Habiyaremye et al., 2022). In the context of 4IR, TVET must transition from traditional manual trades to digitally integrated vocational training. This requires adopting digital tools, smart classrooms, coding, data analytics, AI-driven learning platforms, and online skill certification systems (Penniston, 2021). However, challenges such as funding constraints, lack of qualified lecturers, and limited industry collaboration hinder the full-scale adoption of 4IR in TVET(Els et al., 2022).

Digital Divide

According to Vitalis et al. (2025), the digital divide refers to the gap between individuals, communities, and institutions with access to digital technologies and those without. We concur with Khan (2024), who posit that this divide manifests in several dimensions, including infrastructural disparities, digital literacy levels, affordability of technology, and policy gaps. In South Africa, the digital divide is particularly pronounced in historically disadvantaged TVET colleges and rural communities, where access to high-speed internet, modern digital tools, and industry partnerships is often limited(Boakye, 2024). Alexander (2021), cautioned that excluding digitally marginalised students from 4IR-related TVET training without targeted interventions could reinforce socio-economic inequalities and limit pathways to employment in technology-driven sectors.

Employability

Murrar et al. (2022), elude that employability refers to skills, knowledge, and competencies that enable individuals to secure and maintain employment in a competitive labour market. Search through literature postulates that in the context of 4IR, employability increasingly depends on digital skills, problem-solving abilities, adaptability, and technological fluency(Aboderin & Havenga, 2024; Bodibe, 2023; Ohei & Mantzaris, 2023; Ramnund-Mansingh & Reddy, 2021). As pointed out by Molele et al. (2024), TVET colleges play a pivotal role in enhancing employability by aligning curricula with industry demands and incorporating work-integrated learning (WIL), apprenticeships, and digital literacy training. However, if TVET colleges fail to modernise their offerings, graduates may struggle to compete for jobs in an evolving digital economy (Winberg & Nomgauza, 2023). Therefore, systemic reforms are needed to ensure that TVET graduates are equipped with 4IR-relevant competencies.

Systemic Transformation

Systemic transformation refers to comprehensive, multi-stakeholder efforts to restructure educational institutions, policies, and training frameworks to align with emerging economic and technological trends(Sharp, 2002; Ulrichs et al., 2019). In the case of TVET, systemic transformation involves:

- Curriculum reform to integrate 4IR-related skills.
- Investment in digital infrastructure and lecturer training.
- Strengthening policy frameworks to support industry collaboration.

As noted by Voulvoulis et al. (2022), achieving systemic transformation requires a holistic and coordinated approach involving government, industry, lecturers, and students. In this position paper, we examine the theoretical foundations of systemic change through the human capital theory, technology acceptance model (TAM), and systems theory.

Theoretical Perspectives

Human Capital Theory

Human Capital Theory (HCT) posits that investment in education and skills development enhances economic productivity and individual earnings potential(Afutu-Kotey et al., 2024; La, 2024; Mastromartino, 2024). This theory provides a strong justification for upskilling and reskilling youth through TVET to improve their employability and economic contributions in the context of 4IR in South Africa. Carpenter et al. (2024), avers that, from a policy perspective, HCT underscores the economic imperative of integrating 4IR into TVET. According to Awad (2025), Nations that invest in digital skills development are better positioned to compete in the global economy, reduce unemployment, and drive technological innovation. We concur with Badugela (2024), that if investments in digital education are unevenly distributed, marginalised communities remain excluded from 4IR-driven economic opportunities, deepening the digital divide.

Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM) explains how individuals and institutions adopt and integrate new technologies based on two key factors:

1. Perceived usefulness – The extent to which users believe a technology will enhance their performance.
2. Perceived ease of use – The extent to which users believe a technology is easy to use and requires minimal effort (Ghimire & Edwards, 2024) .

TAM provides valuable insights into why some lecturers and institutions resist or embrace 4IR technologies in the South African TVET sector (Kong et al., 2024). Factors such as lack of training, resource constraints, and institutional inertia affect how TVET colleges incorporate digital tools. Due to concerns over job displacement or lack of digital literacy, resistance to change among lecturers slows the adoption of 4IR learning models.

Systems Theory

According to Leoni (2024), Systems Theory views institutions as interdependent systems where changes in one component affect the entire structure. In the case of TVET, a systems approach recognises that successful 4IR integration depends on the alignment of multiple components:

- Education policy (government regulations, funding mechanisms).
- Industry partnerships (private sector engagement, skills demand).
- Institutional readiness (infrastructure, curriculum development, lecturer capacity) (Harney, 2024).

Recent research reveals that a fragmented approach to 4IR adoption in TVET will not yield sustainable outcomes. Instead, a systems-driven model ensures that digital transformation in TVET is holistic, inclusive, and responsive to labour market needs (Harney, 2024; Lehmann, 2024; Nolan & Owen, 2024).

METHODOLOGY

We employed a systemic literature review (SLR) approach to explore integrating 4IR technologies in TVET. This approach provided a structured and methodical way of synthesizing existing research, offering a rigorous, transparent, and replicable framework for identifying patterns, trends, and research gaps in each field(Karunarathna et al., 2024; Marzi et al., 2024). We decided to adopt this approach driven by the need to critically evaluate existing scholarly discourse on 4IR adoption in TVET, ensuring that the findings contribute to evidence-based policy recommendations and sustainable interventions. Unlike traditional literature reviews, which are often narrative-based and subjective, an SLR follows a predefined methodology to minimize bias and improve reliability and validity(van Riel & Snyder, 2024).

Justification for Using a Systemic Literature Review

An SLR is crucial for synthesizing fragmented research on integrating 4IR technologies in TVET, ensuring methodological rigour and the identification of critical research gaps. As automation, AI, and digital transformation rapidly reshape workforce demands, research remains dispersed across disciplines such as education, economics, and policy studies. By consolidating diverse perspectives, an SLR enables a comprehensive evaluation of TVET's evolving role in the digital economy, particularly in developing contexts like South Africa. This methodology enhances objectivity, replicability, and transparency through predefined inclusion and exclusion criteria, prioritizing peer-reviewed literature from the last decade (2014–2024) that focuses on digital skills, employability, and systemic transformation while excluding studies lacking theoretical or empirical rigor. Utilizing databases such as Scopus, Web of Science, ERIC, and Google Scholar, alongside policy repositories like UNESCO and the World Bank, the research employed a structured keyword search with Boolean operators (AND/OR) to refine relevant studies. Following the PRISMA framework, a multi-stage selection process, including duplicate removal, abstract screening, and full-text eligibility assessment, ensured methodological precision. The selected studies underwent qualitative content analysis, employing a deductive-inductive coding framework to extract key themes, trends, and gaps. This synthesis incorporated descriptive analysis (mapping 4IR adoption trends in TVET, comparative analysis (contrasting developed and developing contexts), and critical analysis (identifying contradictions and policy gaps). Cross-verification with multiple sources and inter-coder reliability checks further strengthened validity and reliability.

OPPORTUNITIES AND CHALLENGES

As posited by Mokofe (2024) 4IR has ushered in a new era of technological advancements, automation, and digital transformation, significantly impacting labour markets, education systems, and vocational training models. Therefore, as economies transition towards knowledge-based and technology-driven industries, the role of TVET in preparing a future-ready workforce becomes increasingly critical (Kana & Letaba, 2024). TVET colleges must modernise curricula, integrate emerging technologies, and develop new pedagogical strategies to equip students with the competencies needed in digitalised work environments.

Opportunities

Digitalisation as a Driver for Curriculum Modernisation

Kana and Letaba (2024) , highlight that one of the most significant opportunities presented by 4IR is the transformation of TVET curricula to align with contemporary industry demands. Traditionally, vocational education has been characterised by hands-on, practical training focused on manual trades and industry-specific skills(Sharma et al., 2024). However, with the rise of automation, AI, and smart manufacturing, there is a growing need to integrate digital literacy, computational thinking, and interdisciplinary problem-solving into TVET programs (Bilbis, 2024; Judijanto et al., 2024). Digitalisation enables adaptive and technology-enhanced learning, fostering personalised and competency-based training. Emerging instructional technologies such as virtual reality (VR), augmented reality (AR), and simulation-based learning offer TVET students immersive, real-world experiences that enhance their technical skills and decision-making abilities(Chen & Chan, 2024). Digitalisation promotes flexible and blended learning models, allowing TVET colleges to reach a broader audience. Through online learning platforms, mobile applications, and cloud-based training, students can access self-paced and on-demand courses, breaking the traditional barriers of time, location, and resource constraints(Kaliraj et al., 2024).

Emerging Skills and Competencies in the 4IR Era

Magagula and Awodiji (2024) suggest that the integration of 4IR technologies into TVET necessitates the development of new skill sets and competencies that extend beyond traditional technical skills. In today's economy, employers prefer individuals with digital, cognitive, and soft skills in contemporary work environments to navigate evolving technological landscapes(Magagula & Awodiji, 2024). The key competencies emerging in the 4IR era include:

- Artificial Intelligence (AI) and Machine Learning (ML): Understanding AI-driven automation processes, predictive analytics, and algorithmic decision-making.

- Internet of Things (IoT): Familiarity with smart devices, networked systems, and sensor-based automation in industrial settings.
- Robotics and Mechatronics: The ability to operate, program, and troubleshoot autonomous machines and robotic systems in advanced manufacturing environments.
- Data Analytics and Cybersecurity: Developing data-driven decision-making skills, understanding big data processing, and ensuring secure workplace digital infrastructures(Aboderin & Havenga, 2024; Blignaut & Botha, 2024).

We concur with Kana and Letaba (2024) incorporating these skills into TVET curricula ensures graduates are equipped for high-demand, future-oriented careers in innovative industries, digital manufacturing, and technology-driven services. Moreover, it enhances learner adaptability, enabling them to transition across multiple career pathways as technology evolves.

Enhancing Employability through Smart Technologies and Work-Integrated Learning (WIL)

Tsephe (2024) argues that another transformative opportunity presented by 4IR is using innovative technologies and digital tools to enhance employability and job readiness. In an increasingly digitalised and automated economy, traditional employment pathways are shifting towards gig work, remote jobs, and hybrid workplace models, necessitating a redefinition of TVET's role in workforce preparation(Dinika, 2024; Wu & Yang, 2024). One of the most effective strategies for improving employability in 4IR is expanding (WIL) opportunities. Sibisi (2024) noted that WIL programs allow TVET students to gain practical, hands-on experience in industry settings, bridging the gap between theory and practice. For Hesselbarth et al. (2024), the advent of remote and digital work environments necessitates a more flexible and technology-driven approach to WIL. TVET students can gain real-world exposure without being confined to traditional physical workspaces through AI-powered career guidance tools, digital apprenticeships, and virtual internships(Colaiacovo, 2024; Stephen et al., 2024).

Epaphras (2025), avers that innovative technologies facilitate on-the-job training and lifelong learning, allowing workers to continually upgrade their skills through micro-credentialing and online learning platforms. This adaptability is particularly crucial in industries where technological advancements require continuous upskilling and reskilling. Tapping on these opportunities, TVET colleges can enhance graduate employability, ensure alignment with industry trends, and contribute to economic sustainability in the digital era(Epaphras, 2025; Hassan & Anees, 2024; Kana & Letaba, 2024).

Challenges

Almeida and Okon (2024), highlight that while the 4IR presents transformative opportunities for TVET, several challenges hinder the seamless integration of digitalisation into vocational education and training systems. These challenges stem from infrastructural limitations, gaps in lecturer preparedness, misalignment between policy and industry demands, and insufficient collaboration between TVET colleges and industries (Mesuwini, 2024). If these barriers are not adequately addressed, the potential benefits of 4IR-driven TVET reforms may remain inaccessible to large population segments, exacerbating existing inequalities and limiting the effectiveness of skills development initiatives.

Infrastructural Gaps and Unequal Access to Digital Tools in TVET Colleges

Ojo and Ndzendze (2024), point out that a significant challenge in integrating 4IR technologies into TVET is the unequal distribution of infrastructure and access to digital tools, particularly in developing economies and rural regions. Many TVET colleges, especially those serving historically disadvantaged communities, continue to struggle with limited internet connectivity, outdated computer laboratories, and insufficient access to industry-grade software and equipment(du Plooy et al., 2025). Infrastructural deficiencies prevent students from engaging in technology-enhanced learning, which is critical for developing digital literacy, computational skills, and technical proficiency in emerging technologies such as robotics, AI, and cloud computing. Moreover, digital disparities between urban and rural TVET colleges create unequal opportunities for skill development, disadvantaging students from resource-poor backgrounds who lack exposure to cutting-edge technological applications(Mbambo & du Plessis, 2025).

The high costs of acquiring and maintaining digital infrastructure pose financial challenges for TVET colleges(Pinto et al., 2025). Establishing smart classrooms, simulation labs, and online learning platforms requires significant investment in hardware, software, and broadband services, which many institutions may find difficult to afford. Without targeted government intervention and public-private partnerships, the digital divide in TVET will persist, limiting the capacity of institutions to produce a workforce that meets the evolving demands of 4IR industries(Karthikeyan & Singh, 2025).

Lecturer Readiness and Training Deficiencies

Denhere and Moloi (2021), posit that the successful integration of 4IR technologies into TVET is highly dependent on the readiness and competence of lecturers. However, many TVET lectures lack the necessary digital skills, pedagogical expertise, and industry exposure to teach technology-driven curricula effectively. For Mbatha (2024), in many cases, TVET lecturers were trained in traditional vocational disciplines, and their knowledge of emerging digital technologies remains limited. This gap in expertise makes it difficult for them to develop and deliver innovative learning experiences that align with 4IR advancements. Professional development opportunities for TVET lectures remain inadequate(Amoo,

2021; Makgato, 2022). Many training programs focus on theoretical knowledge rather than practical applications, leaving lecturers ill-equipped to navigate digital learning environments, integrate innovative technologies into their teaching, or facilitate project-based learning that simulates real-world industry challenges. The lack of structured industry immersion programs for TVET lectures prevents them from staying updated on technological advancements and industry best practices (Majola, 2024). To address these gaps, Makgato (2022) suggest that comprehensive capacity-building initiatives are needed to reskill and upskill TVET lectures. This includes:

- Ongoing digital literacy training to equip lecturers with AI, IoT, cybersecurity, and digital pedagogy competencies.
- Industry exchange programs that allow TVET lecturers to gain hands-on experience in technologically advanced workplaces.
- Professional learning communities and mentorship programs that support peer knowledge-sharing and collaboration among lecturers.

Policy and Curriculum Misalignment with Industry Needs

Mkhize-Simelane (2024) notes that another critical challenge is the disconnect between TVET policies, curricula, and industry demands. The rapid pace of technological change means that many TVET curricula quickly become outdated, failing to incorporate emerging competencies such as data analytics, automation, and digital problem-solving. As a result, graduates often lack the practical skills needed in contemporary work environments, leading to high unemployment rates despite the growing demand for skilled workers in 4IR sectors (Bodibe, 2023). Policy frameworks governing TVET systems often take years to revise, making it difficult for institutions to adapt quickly to industry transformations. Tekle et al. (2024) state that TVET curriculum development follows a bureaucratic process in many countries, where new training programs require extensive regulatory approval before implementation. This slows curriculum innovation, preventing students from acquiring the latest skills in digital manufacturing, smart logistics, and AI-driven services.

Van der Hijden and Martin (2023) advices that lacking national qualification frameworks that accommodate micro-credentials and stackable learning pathways further limits TVET graduates' career mobility. Shaik and Rethman (2025) hold a view that, in the 4IR era, continuous learning and upskilling are essential; however, traditional TVET programs often fail to provide modular, competency-based certifications that allow workers to adapt to changing job markets without committing to full-time studies. To bridge the policy-industry gap, greater collaboration between TVET colleges, policymakers, and industry stakeholders is necessary(Sandri et al., 2024). This includes:

- Agile curriculum development processes that allow for frequent updates in response to technological changes.
- Industry-aligned certification systems that integrate short courses and micro-credentials into formal qualification frameworks.
- Public-private partnerships that facilitate co-designed training programs, ensuring relevance to industry needs.

Limited Industry-TVET Collaboration for Digital Skill Development

A significant barrier to 4IR-driven TVET transformation is the limited collaboration between TVET colleges and industries in designing and delivering technology-based training program(Legg-Jack & Ndebele, 2022).Chanda (2023) notes that while industries are at the forefront of technological advancements, TVET colleges often operate in isolation, resulting in misaligned training approaches that do not reflect real-world workplace demands. Many TVET programs fail to provide students with hands-on experience in smart factories, AI-driven logistics, or cloud-based service environments because formal linkages with industries remain weak(Lukhele & Laseinde, 2024). As a result, graduates enter the job market with theoretical knowledge but limited practical exposure, making them less competitive in high-tech employment sectors. Employers often perceive TVET graduates as underprepared for digital workplaces, leading to reluctance to hire them for technology-intensive roles(Papier, 2021). To strengthen industry-TVET collaboration, the following strategies are crucial:

- Industry-led training consortia that co-develop curricula, learning resources, and certification frameworks aligned with emerging technological trends.
- Stronger work-integrated learning (WIL) partnerships where TVET students gain exposure to real-world digital applications through internships, apprenticeships, and on-the-job training.
- Establish technology hubs within TVET colleges, where industries provide cutting-edge tools, mentorship, and innovation-driven learning experiences(Winberg & Nomgauza, 2023).

Despite the promising opportunities that 4IR presents for TVET, significant challenges must be overcome to harness its potential fully. Addressing infrastructural disparities, lecturer preparedness, policy alignment, and industry collaboration is essential for building a resilient and future-ready TVET system(Chanda, 2023). A concerted effort involving governments, educational institutions, industry leaders, and international partners is required to develop inclusive, adaptive, and technologically advanced vocational education models that equip students with the skills needed for sustainable employment in the digitalised world**.**

POLICY AND STRATEGIC RECOMMENDATIONS

To ensure that the TVET colleges effectively adapt to the demands of the 4IR, targeted policy interventions and strategic initiatives must be implemented(Kana & Letaba, 2024). Addressing the infrastructure gap, strengthening lecturer

capacity, transforming curricula, fostering industry partnerships, and enacting policy reforms will equip TVET graduates with future-ready skills. The following recommendations provide a roadmap for enhancing the digital preparedness, employability, and sustainability of TVET in the digital era.

Investment in Digital Infrastructure and Connectivity

One of the most pressing challenges in integrating 4IR technologies into TVET is the unequal access to digital infrastructure and connectivity, particularly in rural and under-resourced institutions(Legg-Jack & Ndebele, 2022; Tondi, 2023). Without modern learning environments, digital laboratories, and high-speed internet connectivity, students lack exposure to innovative technologies, limiting their ability to develop critical digital competencies. To bridge this gap, government and private sector investments in TVET infrastructure must focus on:

- Expanding broadband access to ensure reliable internet connectivity in all TVET colleges, enabling access to cloud-based learning platforms, online simulations, and virtual collaboration tools.
- Upgrading digital laboratories with AI-driven software, IoT devices, automation tools, and industry-standard equipment to enhance experiential learning.
- Providing affordable digital devices (e.g., laptops, tablets) for TVET students and faculty to facilitate hybrid and online learning.
- Developing Open Educational Resources (OERs) to support cost-effective, self-paced digital learning and bridge knowledge gaps (Ralushai, 2021).

Training TVET lectures in 4IR Technologies

TVET lectures play a pivotal role in shaping the technological competencies of students. However, many lectures lack the digital skills to effectively teach 4IR-relevant content, as their professional training often predates the emergence of automation, artificial intelligence, and digital fabrication technologies (Els et al., 2022). To build lecturer capacity, national training programs must focus on:

- Continuous professional development (CPD) programs to train lecturers in emerging fields such as cybersecurity, robotics, cloud computing, and augmented reality.
- Blended learning pedagogical training, equipping lectures with the skills to integrate digital tools, AI-driven assessments, and e-learning platforms into teaching.
- Industry immersion programs that allow TVET lecturers to gain hands-on experience in high-tech industries, enabling them to align teaching with real-world technological applications.
- Create digital peer-learning networks where TVET lectures collaborate, share best practices, and mentor each other using 4IR technologies(Hani et al., 2024).

Aligning TVET Courses with 4IR Competencies

The mismatch between traditional TVET curricula and the skills demanded by 4IR industries is a key factor contributing to graduate unemployment and skill shortages. To ensure that TVET students are work-ready, there is an urgent need to modernise curricula and integrate digital literacy, automation, and data-driven problem-solving skills into vocational training(Sey & Mudongo, 2021). Key curriculum reforms should include:

- Embedding digital skills training across all TVET disciplines, ensuring that students develop fundamental to advanced competencies in AI, IoT, blockchain, and digital manufacturing.
- Introducing interdisciplinary learning, combining technical and soft skills such as critical thinking, adaptability, and digital collaboration to enhance employability.
- To improve practical understanding and incorporate project-based and problem-solving approaches using real-world simulations, industry case studies, and virtual reality-based learning.
- Creating flexible learning pathways, including micro-credentials, stackable certifications, and competency-based learning models to accommodate lifelong skill development and career progression(Moleko, 2022; Soupramanien & Rughoobur-Seetah, 2024).

Strengthening Industry-TVET Partnerships: Work-Based Learning in Digital Sectors

Vuthela and Ngumbela (2024), notes that a significant limitation of TVET training is students' lack of hands-on industry exposure. Many TVET graduates struggle to transition into employment because they lack practical experience with digital work environments, smart factories, and automation-driven industries(Mayombe, 2024a). Strengthening TVET-industry collaboration is crucial to bridging the gap between education and employment. Key strategies to enhance work-based learning in digital sectors include:

- Expanding apprenticeship and internship programs in AI-driven industries, software engineering firms, renewable energy sectors, and innovative manufacturing plants.
- Establishing industry-aligned innovation hubs within TVET colleges, where companies provide students hands-on experience in digital prototyping, programming, and automation.
- Developing co-designed curricula, where industry experts contribute to curriculum development, guest lectures, and mentorship programs to ensure relevance.

- Encouraging public-private partnerships, where tech companies sponsor digital upskilling programs, equipment donations, and work-based learning scholarships(Govender & Dhurumraj, 2024; Magagula & Awodiji, 2024; Mayombe, 2024b).

Government Support for Sustainable and Inclusive 4IR Adoption

Sustainable adoption of 4IR technologies in TVET requires strong policy frameworks that promote digital inclusivity, long-term investments, and regulatory alignment with labour market demands (Mbaluka & Munyifwa; Mtotywa et al., 2024). Governments must proactively shape TVET systems that support technological adaptation and equitable access to skills training (Majola, 2024). Key policy interventions include:

- Developing national digital skills strategies, outlining clear 4IR competency benchmarks and learning pathways for TVET colleges.
- Providing financial incentives (grants, subsidies, tax breaks) for TVET colleges and companies that invest in digital training programs, e-learning infrastructure, and smart technologies.
- Implementing regulatory frameworks for micro-credentialing, ensuring that short-term courses and stackable digital qualifications are recognised in national and international job markets.
- Promoting gender-inclusive policies, ensuring women and marginalised groups have equal access to 4IR skills training to bridge gender gaps in STEM and digital fields.

Governments can drive systemic transformation in TVET by enacting progressive policies and ensuring sustainable, inclusive, and future-ready vocational education models. The 4IR is reshaping labour markets, and TVET colleges must adapt rapidly to meet these changing demands(Kana & Letaba, 2024). Sele and Mukundi (2024), advise that by bridging infrastructure gaps, building lecturer capacity, modernising curricula, strengthening industry collaborations, and enacting strategic policy reforms, TVET can catalyse inclusive economic growth, youth employability, and sustainable development in the digital age.

CONCLUSION

The 4IR necessitates a fundamental transformation in TVET to remain relevant in an increasingly digital economy. This paper highlights the opportunities presented by 4IR, including curriculum modernization, enhanced employability, and work-integrated learning, while exposing critical challenges such as infrastructural deficits, policy misalignment, and weak industry collaboration—particularly pronounced issues in developing contexts like South Africa. A multi-stakeholder approach requires strategic government investment, robust private-sector partnerships, and progressive policy frameworks to bridge the digital divide. South Africa's TVET colleges must embrace a proactive, evidence-based strategy prioritising infrastructure modernization, lecturer capacity development, industry alignment, and sustainable policy reforms to drive economic innovation and reduce youth unemployment. Future research should focus on empirical, longitudinal analyses of 4IR adoption in TVET to assess its tangible impact on employability, economic participation, and digital equity. Comparative studies benchmarking South Africa's TVET strategies against global best practices could yield critical policy insights.

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