The Symbiotic Dance: A Conceptual Analysis of Mobile Connectivity and AI for Sustainable Societal Development in Southern Africa

Dr Tabani Moyo - ORCID: 0000-0001-5201-3370
Extra-Ordinary Researcher – School of Social Transformation
North-West University, Potchefstroom Campus
South Africa
African Union Working Group on Artificial Intelligence Member
moyojz@gmail.com

Dr Farai Chigora - ORCID: 0000-0002-8932-3601
Extraordinary Special Researcher in
School of Management Sciences
North-West University, Potchefstroom Campus
South Africa
fariechigora@gmail.com
Dr Beaullah Chirume – Communications & Technology Policy Specialist, in Collaboration with North-West University Business School
chirume.beaullah@gmail.com
Professor Cecile Proches Gerwel - ORCID: 0000-0002-2330-9575
University of KwaZulu-Natal, Graduate School of Business & Leadership (GSB&L)
Gerwel@ukzn.ac.za
Professor Emmanuel Mutambara - ORCID: 0000-0002-8030-9061
PhD Programme Leader
North-West University, School of Business, Potchefstroom Campus
South Africa
Emmanuel.Mutambara@nwu.ac.za
Mr Amr Safwat
North-West Business School in collaboration with African Union Working Group on Artificial Intelligence
asafwat@mcit.gov.eg

Introduction

This conceptual analysis, The Symbiotic Dance, examines mobile connectivity and artificial intelligence as mechanisms for sustainable societal development in Southern Africa, focusing on how mobile connectivity enhances community progress by enabling new technology. The analysis explores global mobile technology trends and advancements, especially in Southern Africa, demonstrating how mobile phone technology influences other technologies impacting society. The paper argues that the synergistic interaction among the mobile connectivity layer, AI development and deployment layer, and the contextual and governance layer drives social growth in Southern Africa. Mobile broadband technology has rapidly improved African socioeconomic conditions, increasing smartphone use and network proliferation (Akinlabi & Dahunsi, 2021). In Sub-Saharan Africa, mobile subscriptions reached 527 million by 2023, and smartphone usage is projected to reach 786 million by 2029 (Azeez et al., 2025). Despite this rapid growth, many Africans remain disconnected from the global digital world (Doerksen et al., 2024).

Due to differences in technological infrastructure, some countries have established digital ecosystems while others struggle with connectivity and digital literacy (Adeleye et al., 2024). In Southern Africa, poor broadband penetration and service quality hinder growth and development (Robb &Paelo, 2020). This article intensively examines Southern Africa's mobile connection difficulties and potential, emphasising on infrastructure, network quality, coverage, and device capabilities.

Mobile connectivity is often touted as a solution for digital inclusion in Africa, but reports on universal mobile access often misrepresent reality, especially in Zambia and Zimbabwe, where ‘mobile' operators' networks are the only widely accessible two-way communication infrastructure (Stam, 2021). Mobile infrastructure is crucial to bridging communication gaps, especially in rural areas with limited alternatives (Mwansa et al., 2025; Robb &Paelo, 2020).

Historical socio-economic inequality, poor rural broadband investment, power outages, and low digital literacy increase these inequalities, especially in rural and low-income areas (Oladunjoye& Chaka, 2025). This study will examine Southern Africa's mobile infrastructure, network quality, coverage, and device capabilities and their influence on AI integration. It will also offer equitable digital inclusion strategies.

To comprehensively analyse the intricate relationship between mobile connectivity and AI for development in Southern Africa, this study will utilise established theoretical frameworks to provide a solid analytical perspective. Specifically, the Diffusion of Innovations theory, the Capability Approach, and the Structuration Theory will be employed to assess how these technologies are introduced, adopted, and embedded into the region's unique socio-technical contexts.

Southern African Mobile Connectivity Context

The diverse economies and varying levels of technology across the Southern African Development Community region pose challenges for mobile connectivity research (Duca et al., 2024). Although mobile network expansion has advanced, insufficient infrastructure, geographic remoteness, and socioeconomic barriers limit access to information and communication technologies in many rural areas (Mwansa et al., 2025). Rural regions such as the Eastern Cape Province in South Africa face significant digital exclusion (Mwansa et al., 2025). Understanding the infrastructure, network quality, and socio-economic factors influencing mobile connectivity adoption in these settings is essential to addressing this disparity.

Discussions on digital inclusion emphasise the need to close the connectivity gap by improving access, lowering costs, and enhancing digital literacy across regions (Ehimuan et al., 2024). While 5G offers high-speed connectivity, deploying it in rural areas to support sustainable development and digital inclusion poses challenges and raises potential solutions (Farinha & Martins, 2025). The potential for 5G to transform agriculture through precision farming and automation warrants thorough analysis in Southern Africa (Farinha & Martins, 2025).

Mobile connectivity, beyond basic access, enables marginalised farming communities to reach digital markets and achieve financial inclusion, thereby supporting agribusiness and rural development (Fausiyat, 2025). It can help reduce inefficiencies arising from fragmented markets, poor infrastructure, and limited financial services in Sub-Saharan African agribusiness (Fausiyat, 2025). Mobile finance ecosystems, government subsidies, and climate insurance schemes can help these communities manage market volatility and the impacts of climate change (Fausiyat, 2025). Mobile technology facilitates farmers' access to finance, insurance, savings, and real-time market information, alleviating financial exclusion caused by geographical isolation and inadequate traditional banking infrastructure (Fausiyat, 2025). Digital financial tools, such as digital wallets, mobile credit scoring, and blockchain-based payment systems, address credit barriers and reduce reliance on informal financing in these areas (Fausiyat, 2025).

The integration of mobile and FinTech innovations boosts agricultural productivity and financial inclusion in Sub-Saharan Africa (Glavanits& Szabó, 2024). This development creates resilient digital market platforms that connect rural farmers directly to customers and larger marketplaces, cutting out intermediaries and enhancing profitability and market efficiency (Fausiyat, 2025). Mobile connectivity also supports remote education, healthcare, and agriculture, thereby strengthening human capital and community well-being (Mothobi&Kebotsamang, 2024). Technologies such as mobile money have increased market participation and financial inclusion among smallholder farmers (Ky, 2025; Nwangwu et al., 2024). FinTech solutions support pre-production financing and help ensure fair harvest pricing for smallholder farmers, helping to prevent exploitation along the value chain (Rayhan et al., 2024). These technological advances can also address climate change risks and regional food security, transforming the sector (Asante et al., 2025). Furthermore, digital technologies provide farmers with immediate access to weather forecasts and pest alerts, enabling more accurate and adaptable decision-making (Lyu et al., 2025). Financial technology solutions enable smallholder farmers to access funding, digital payment systems, and market information, boosting productivity and fostering participation in larger agri-food markets (Adesiyan, 2025; Mapanje et al., 2023).

Problem Statement

Despite these achievements, significant gaps in mobile connectivity across Southern Africa hinder equitable access to transformative FinTech and agricultural technologies (Hornuf et al., 2024). The lack of internet access and infrastructure disproportionately affects rural populations, exacerbating economic inequalities and constraining sustainable development (Choruma et al., 2024). These gaps hamper the adoption of digital platforms that could enhance agricultural output and revenue through improved decision-making, market access, and financial transactions (Choruma et al., 2024; Panwar & Sahoo, 2025). These issues emphasise the need for targeted interventions and policies to upgrade mobile infrastructure and digital literacy, ensuring that all social groups can benefit from technological progress (Abdulai, 2022; Abdulai et al., 2023). This study will explore the complex challenges and opportunities of mobile connectivity in Southern Africa, including its role in agribusiness growth and rural development. It will investigate how digital transformation, particularly FinTech, can address funding, financial inclusion, and market-entry barriers within agricultural value chains in developing countries (Zhang, 2024). The research will analyse how policy frameworks, infrastructure enhancements, and device capabilities foster an

inclusive digital environment that supports sustainable agriculture and the livelihoods of smallholder farmers (Choruma et al., 2024; Rayhan, 2024).

Research Questions

- How does mobile network infrastructure availability and quality affect FinTech adoption in rural Southern Africa?
- How do rural people's device and digital literacy barriers impact their participation in mobile-enabled agricultural and financial services?
- Which policies and regulations are most effective at closing the digital divide and promoting inclusive mobile coverage in Southern African agriculture and rural development?
- How can public-private partnerships accelerate resilient mobile infrastructure and digital literacy for Southern African smallholder farmers?
- How do FinTech and mobile connectivity boost agricultural production and food security in Southern Africa, especially for at-risk smallholder farmers?
- How do socio-economic factors and financial exclusion affect mobile connectivity and FinTech adoption in rural agricultural areas of Southern Africa?

Literature Review

This section builds on previous research to develop a theoretical framework for understanding the complex relationship between mobile connectivity, FinTech, and agricultural growth in Southern Africa, highlighting existing gaps (Zhang, 2024). It carefully evaluates socio-technical, systemic, and infrastructural barriers faced by small-scale farmers in adopting agricultural technologies and digital financial services (Manning, 2024; Smidt & Jokonya, 2021). This analysis investigates how digital agriculture ecosystems can help smallholders overcome financial resource constraints and information access barriers (Gumbi et al., 2023).

The study examines how mobile connectivity helps bridge the digital divide in rural areas, thereby enhancing financial inclusion and access to financial services for previously unbanked communities. For initiatives promoting financial inclusion in Sub-Saharan Africa, understanding the factors that influence mobile FinTech adoption is vital (Hornuf et al., 2024). The literature underscores the importance of effective policy measures to support inclusive digital agriculture, particularly for smallholder farmers (Mazwane et al., 2022). To realise these benefits, it is essential to recognise challenges such as limited internet access, poor infrastructure, and low digital literacy in Southern Africa (Choruma et al., 2024). This knowledge supports the development of targeted interventions to address the specific limitations faced by smallholder farmers, fostering sustainable agricultural growth through technological integration (Gumbi et al., 2023).

Understanding how performance and effort expectations, societal restrictions, and enabling factors shape the adoption of digital financial services among rural farming communities is essential (Wang et al., 2023). Digital agriculture, supported by reliable mobile connectivity, can help address issues related to climate change, productivity, and access to loans that affect smallholder farmers (Gumbi et al., 2023). Although digitalisation offers significant potential for smallholder farmers in Sub-Saharan Africa, further research is needed to clarify which digital technologies are used and the challenges they face (Choruma et al., 2024). This

requires a comprehensive assessment of digital agriculture practices and their obstacles, including digital literacy gaps and infrastructural barriers that hinder the deployment of advanced digital solutions (Gumbi et al., 2023). It is also crucial to examine how digital technologies can promote agricultural sustainability in developing countries by identifying and closing knowledge gaps regarding smallholder farmers' access to technologies and services (Mushi et al., 2022). This includes examining the digital divide and its impact on equitable access to digital agro-advisory tools, which are vital for sustainable agricultural development (Ofosu-Ampong et al., 2025; Yang & Sun, 2024).

Mobile Connectivity Conceptual Framework

This section outlines the core concepts and models of how mobile connectivity affects agricultural productivity and financial inclusion in Southern Africa. For a comprehensive analysis, it incorporates technology adoption theories, such as the Unified Theory of Acceptance and Use of Technology (Nkandu & Phiri, 2022), and frameworks addressing the digital divide. The adoption of mobile-enabled FinTech solutions by smallholder farmers is influenced by perceived utility, convenience, social influence, and supportive conditions (Nkandu & Phiri, 2022). This paradigm also examines how trust, risk perception, and socio-economic disparities shape the adoption of mobile connectivity and its effects on rural livelihoods. It considers the influence of government policies and regulations on mobile connectivity in marginalised farming communities. Infrastructure development and network quality theories are integrated into the conceptual framework, as they facilitate widespread mobile access and reliable digital services across diverse landscapes (Gumbi et al., 2023). Additionally, the study explores how smartphone adoption and feature phone use affect access to and utilisation of mobile-based agricultural applications and financial instruments. It investigates the complex relationships between technology, user behaviour, and policy in promoting agricultural progress and economic empowerment through mobile connectivity (Engås et al., 2023; Sen et al., 2025). The analysis also critically assesses mobile network infrastructure and its impact on dependable access to digital services, particularly in rural agricultural regions. This includes evaluating 3G, 4G, and 5G network resilience, coverage, spectrum allocation, and regulatory frameworks that influence network expansion and quality (Mazwane et al., 2022). Moreover, it analyses how network quality—latency, bandwidth, and reliability—affects smallholder farmers' utilisation of digital agricultural tools and FinTech services (Muromba et al., 2025).

The framework further examines the connection between perceived ease of use and perceived usefulness, which are vital factors in rural FinTech adoption, often driven by innovation and financial literacy (Wu & Peng, 2024). The approach incorporates household production theory, suggesting that labour-enhancing technologies such as mobile FinTech and agricultural applications increase land productivity by improving information and resource management (Wang et al., 2025). Mobile connectivity can help smallholder farmers increase agricultural productivity and sustainability by providing timely market information and resource allocation (Nwafor, 2020). The success of digital solutions largely depends on their compatibility with community practices and skills, so producers with limited digital literacy need a simple technology design approach (Paget et al., 2025). Since community radio and mobile phones are the most cost-effective and widely used, they should be utilised to share agricultural knowledge and sustainable practices with smallholders (Ngulube, 2025). Recent studies highlight a growing focus on productivity-

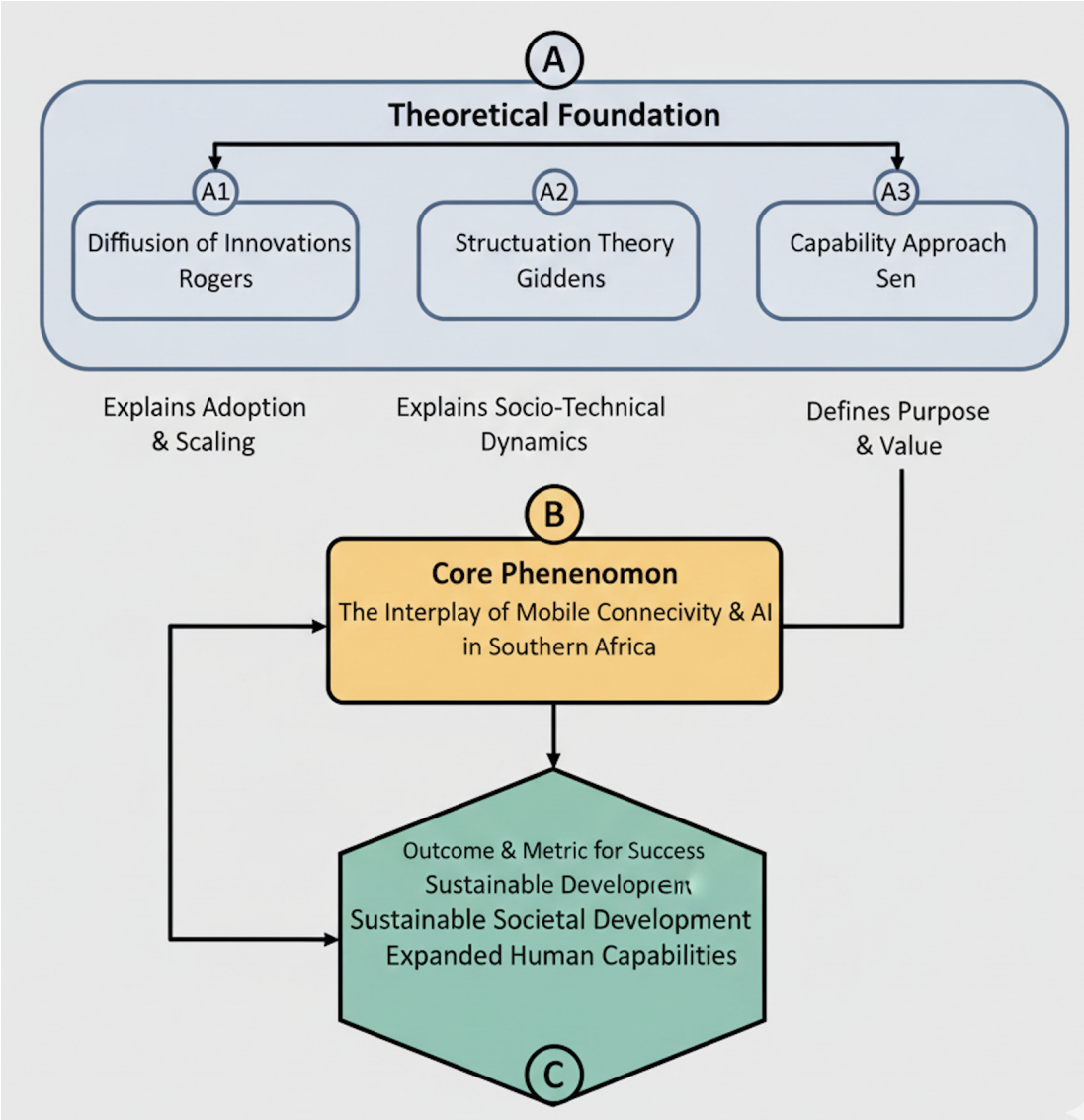
driven ICT deployment; however, smallholder farmers often prefer low-tech digital options due to familiarity (Bontsa et al., 2023).

Development-focused AI

AI has the potential to advance Southern Africa beyond traditional development stages but deploying it in resource-limited settings requires a nuanced understanding (Boateng, 2024). This entails overcoming infrastructure barriers, ensuring access to relevant datasets, and training a skilled workforce to develop, implement, and maintain AI systems across diverse local contexts (Xiao et al., 2025). Additionally, model hallucinations and factual distortions could undermine the effectiveness of AI tools in critical sectors such as education and healthcare, underscoring the importance of reliability (Segun et al., 2025). Poor electrical infrastructure may cause frequent system outages, reducing the usefulness of AI diagnostic or triage technologies and casting doubt on their medical forecasting accuracy (Segun et al., 2025).

The unreliability of AI in education, particularly in mathematics, raises concerns about its role as a personalised teacher, casting doubt on its accuracy and dependability (Segun et al., 2025). The Western-dominated discourse on large language models often overlooks Southern Africa's unique linguistic diversity and cultural nuances, resulting in poor performance in local languages and dialects (Moorosi, 2024). Many AI tools are developed in English or other widely used languages, ignoring the linguistic diversity of the Global South (Makeleni et al., 2023). This limits accessibility and perpetuates the digital divide, making it harder to adopt inclusive and representative AI solutions aligned with local cultural and socio-economic conditions. Consequently, AI-driven language-teaching methods tailored to learners' needs and contexts in the Global South, including the promotion of local languages, should be prioritised (Makeleni et al., 2023).

The conceptual framework is summarised in Figure 1 below :



Source: Researchers' own construction 2025: The symbiotic dance: A Conceptual Analysis of Mobile Connectivity and AI for Sustainable Societal Development in Southern Africa conceptual framework

a) Theoretical Foundation
The theoretical foundations are based on three main theories: the diffusion of innovation, structuration, and capability theories. This shapes the paper within a framework of arguments centred on the adoption and scaling of technology in society. Through the structuration theoretical lenses, the paper grounds its inquiry in socio-technical dynamics in society. At the same time, the capabilities approach shapes the values and purpose of a technology being deployed and developed in society.

b) Core phenomenon
Predicated on the foregoing theoretical frameworks, component (b) of the conceptual framework shapes and unpacks the interplay between mobile connectivity and technological developments such as AI, and how these are evolving

in Southern Africa. This relationship is denoted in the symbiotic dance, with the former influencing the latter.

c) Outcome & metric for success
The last component of the conceptual framework unpacks how this symbiotic dance affects societal development and enhances human development capabilities.

Theoretical Framework

Technology Adoption Theories

This research examines the complex relationship between mobile connectivity and AI for Southern African development using current theoretical frameworks. The Diffusion of Innovations theory, Capability Approach, and Structuration Theory will be employed to explore how these technologies are introduced, adopted, and integrated into the region's socio-technical contexts. Adıgüzel et al. (2023) and Valdivieso & González (2025) provide distinct yet complementary insights into how mobile and AI technologies are distributed, adopted, and ultimately transform societal and individual perspectives. Everett Rogers' Diffusion of Innovations theory describes how new ideas and technologies spread within social systems, illuminating the rates of mobile connectivity and AI adoption in Southern Africa.

This thinking suggests that perceived attributes of innovations, communication channels, and social systems influence patterns of adoption, which is vital to understanding why various Southern African cultures embrace modern technology. Conversely, Amartya Sen's Capability Approach emphasises individuals' real capabilities and potential, assessing the actual effects of mobile and AI access on human wellbeing and development in the region. This study goes beyond mere technological access to explore how mobile technology and AI help people reach their potential and enjoy meaningful freedoms. Anthony Giddens' Structuration Theory illustrates how mobile and AI technologies influence and are influenced by social practices and institutions in Southern Africa. This comprehensive theoretical framework enables a detailed analysis of how mobile connectivity and AI are deeply entwined with the region's social, economic, and political fabric, shaping and being shaped by power structures and developmental pathways.

The Technology, Organisation, and Environment framework, together with Diffusion of Innovations theory, provides a broad perspective on AI adoption, particularly for mobile-based services in emerging economies. Bourdieu's Theory of Practice, particularly its concepts of field, capital, and habitus, clarifies how power relations and symbolic systems shape reality and how these technologies are integrated into everyday life (Bisimwa et al., 2018). This multi-theoretical approach will enable a comprehensive analysis of socio-technical factors that hinder or facilitate the widespread and fair use of AI and mobile technologies for sustainable development in Southern Africa (Alka'awneh et al., 2025). The Technology Acceptance Model and the Theory of Reasoned Action will be used to evaluate end-users' perceptions of usefulness and ease of use, which are essential for AI adoption and mobile AI applications in Southern Africa (Salaheldin& Hussein, 2025).

Capability Approach

This approach goes beyond analysing technology availability to examine how mobile and AI breakthroughs genuinely empower individuals to enhance their "functionings" and capabilities within their unique socio-economic contexts (Mienye et al., 2024). Given Southern Africa's diverse environment and inherent inequalities, this offers a critical perspective for evaluating whether these technologies genuinely improve people's lives (Ndemo& Weiss, 2017). Such a viewpoint is essential for understanding the real impacts of AI and mobile connectivity beyond adoption statistics, including quality-of-life improvements and self-determination (Samuel-Okon & Abejide, 2024). This framework assesses AI's influence on socio-economic issues and development by analysing its applications in healthcare, agriculture, finance, and education (Gikunda, 2024).

Innovation Diffusion Theory

Everett Rogers' Diffusion of Innovations theory is essential for understanding the dynamics and factors shaping the diffusion of mobile connectivity and AI in Southern Africa, particularly their integration into diverse social systems (Adel, 2024). Through perceived ease of use and usefulness, emerging technologies such as AI in e-learning spread within societies, transforming digital literacy and educational methods (Muawanah et al., 2024). It also offers a systematic approach to studying adoption rates, the characteristics of early adopters, and barriers to the widespread uptake of these innovations across diverse cultural and economic contexts (Abulail et al., 2025). This involves examining how contextual factors, individual initiatives, and perceived usefulness, ease of use, compatibility, observability, and trialability influence the adoption of mobile-based AI services in small and medium-sized manufacturing enterprises. The model illustrates how communication channels and social networks disseminate information and shape adoption decisions, especially in areas with varying infrastructure and levels of digital literacy. This theory is particularly significant in Southern Africa, where technological infrastructure and socioeconomic inequalities can significantly affect the integration of AI and mobile technologies into daily life and industrial operations (Ishengoma& John, 2024).

Structuration Theory

Giddens' Structuration Theory offers a comprehensive framework for examining the dynamic interplay between human agency and institutional structures in Southern Africa's mobile connectivity and AI deployment, both of which are products and catalysts of social practices. This perspective shows how social system regulations and resources shape AI acceptance and utilisation, while individual and organisational behaviours can alter these frameworks (Jejeniwa et al., 2024). This recursive relationship indicates that AI and mobile technologies are crucial to social construction and transformation within the region. It posits that expected outcomes shape people's use of modern technologies, although critics argue it does not fully address human behaviour (Sehlako et al., 2023). Nonetheless, structuration theory remains vital to understanding how AI integration into organisational practises modifies routines and power dynamics, particularly in Southern Africa (Dönmez et al., 2025). This framework effectively analyses how facilitators and barriers influence AI adoption across various sectors (García-Vidal et al., 2025; Kajiita& Kang'ethe, 2025). A comprehensive understanding is essential for developing policies that foster equitable and sustainable use of AI and mobile technologies, aligned with the socio-cultural and economic context of Southern Africa (Gikunda, 2024). By employing the Capability Approach, Diffusion of

Innovations Theory, and Structuration Theory, this broad theoretical framework investigates the complex dynamics of AI adoption and its developmental impact in Southern Africa, moving beyond technological determinism to explore socio-technical co-evolution.

This is summarised in Table 1 below:

Analysis Dimension	**Capability Approach Lens**	**Diffusion of Innovations Lens**	**Structuration Theory Lens**	**Integrated Analysis for Southern Africa**
Infrastructure & Access	Focus on capabilities enabled by access: communication, information, banking.	Complexity & Compatibility: Smartphones are complex and costly. AI apps must be compatible with variable network quality (3G/4G) and feature phones via USSD/ SMS.	Structure: Market structures lead to high data costs. State agency regulates spectrum. Agency: Community networks and solar-charging solutions emerge.	The high cost of data and smartphones is a structural barrier that limits the capability-enhancing potential of data-intensive AI. Diffusion requires low-complexity, low-dataAI solutions.
Data for AI	AI must be trained on data that represents local realities to avoid reinforcing biases and eroding capabilities of marginalized groups.	For AI to have a Relative Advantage, it needs large, local datasets. The complexity of building these datasets is a major barrier to diffusion.	Structure: Market structures lead to high data costs. State agency regulates spectrum. Agency: Community networks and solar-charging solutions emerge.	The scarcity of local, representative data is a critical constraint. Without proactive agency(e.g., creating national data strategies), existing social structures (inequality) will be baked into AI systems, harming the capabilities of the poor.
Financial Inclusion (e.g., AI-powered Credit Scoring)	Enhances the capability for economic participation and resilience for the unbanked.	Relative Advantage is huge for those excluded from formal finance. Compatibilityis high if built on top of mobile money platforms (e.g., EcoCash, MPesa).	Agency: Fintech startups are driving this innovation. Structure: Central banks are scrambling to create new regulatory frameworks (sandboxes, digital credit guidelines).	The rapid diffusion of AI-fintech is actively structuring a new financial landscape. The challenge for policymakers (agency) is to ensure this new structure enhances capabilities without leading to predatory lending or algorithmic discrimination.
Healthcare (e.g., AI Diagnostic Tools)	Expands the capability to "be healthy" by improving access to accurate diagnosis in underserved areas.	Trialability & Observability: Success stories from community health workers will be key to diffusion. Complexity must be low for frontline workers.	Structure: Professional medical bodies and government health policies must approve and integrate these tools. Agency: Health workers can choose to adopt or bypass the technology.	The tool's success depends not just on its technical relative advantage, but on how it is integrated into the existing health structureand whether it empowers the agency of health workers, ultimately

				expanding patient capabilities.
Policy & Regulation	The goal of policy should be to steward the technology towards capability expansion for all, not just economic growth.	Regulations can directly affect the Relative Advantage (e.g., subsidies), Complexity(e.g ., privacy rules), and Compatibility (e.g., mandating interoperability) of new AI services.	Policy is the primary formal structureintended to shape technological agency. However, the pace of technology often outstrips the pace of policymaking.	Southern African governments face a structuration challenge: they must use their agency to build agile, enabling structures(policy) that foster innovation while protecting citizens, ensuring the mobile-AI synergy truly diffuses to enhance societal capabilities.

Mobile Infrastructure Improvement in Developing Regions

Mobile infrastructure in developing nations, particularly in Southern Africa, has expanded rapidly, yet coverage and quality remain uneven, especially in rural and neglected areas. Despite progress, many smallholder farmers in these regions struggle to access digital advisory tools because of poor network infrastructure, high device costs, and limited mobile services (Hove et al., 2024). Digitalisation services, ranging from basic mobile communication to advanced drone and satellite technologies, can boost productivity and streamline operations for smallholder farmers in sub-Saharan Africa, yet adoption has been slow and inconsistent (Mhlanga & Ndhlovu, 2023). Poor internet connectivity limited digital literacy, and weak infrastructure hinder uptake (Choruma et al., 2024). These issues deepen the digital divide and hamper agricultural ICT programmes designed to support smallholders' digitalisation (Yang & Sun, 2024). Many developing countries' digital ecosystems for these modern technologies remain underdeveloped, favouring larger commercial entities over smallholder and women farmers (Ngulube, 2025). As a result, infrastructure, policies, and user skills continue to prevent a significant portion of tropical Africa's population, especially the impoverished, from benefiting from these technologies (Ngulube, 2025).

Smallholder farmers often cannot fully utilise digital advisory services, particularly SMS-based ones, because of high data costs and limited access to mobile devices (Hove et al., 2024). Many smallholder farmers in developing countries also lack digital literacy, which hampers the use of digital technologies in agriculture (Choruma et al., 2024; Olorunfemi, 2024). The knowledge hierarchy tends to favour capital-intensive farms over smallholders, owing to constrained digital literacy and budgets (Choruma et al., 2024). Female and elderly farmers often report lower digital literacy and struggle to afford internet and mobile devices (Kansiime et al., 2021). Infrastructural and educational deficits hinder marginalised groups' access to agricultural knowledge and FinTech solutions, perpetuating economic inequality (Abdulai et al., 2023; Khan et al., 2024). For inclusive digital transformation in agriculture, enhancing digital literacy—particularly among marginalised groups—and ensuring

affordable, accessible digital infrastructure are essential to address this disparity. These issues demand a comprehensive strategy that promotes digital literacy and rural connectivity to ensure equitable access to mobile technology (Alfonsi et al., 2024; Ngulube, 2025). Solutions must also confront smallholder farmers' constraints, such as the high costs of digital technology and the need for reliable, context-specific information (Aker et al., 2016; Oklikah, 2023). To motivate smallholders to adopt digital technology, governments should foster financial inclusion through targeted microfinance schemes, digital literacy programmes, and improved extension services (Kitole et al., 2023).

This holistic approach would address policy issues in digital agriculture and the shortage of relevant digital applications, enabling smallholder farmers to embrace digital transformation (Yang & Sun, 2024). An inclusive strategy is vital for smallholders to benefit from digital technologies, enhancing food security and promoting sustainable agriculture (Arangurí et al., 2025). To prevent innovations from deepening disparities among diverse user groups, power dynamics in digital production and distribution must be carefully examined (Hackfort, 2021; Steinke et al., 2024). Without deliberate fair access policies, digital change could exacerbate inequalities, especially for marginalised groups (Tilley et al., 2024). Innovative policies and strategic initiatives are crucial to reducing the costs of coordinating digital transitions and ensuring equitable access for all stakeholders (Kumar et al., 2022). This requires ongoing awareness campaigns and skills-development programmes within formal and informal educational contexts to improve digital literacy and competence (Matchaya et al., 2024). These efforts will foster an inclusive digital landscape for smallholder farmers in Southern Africa, boosting agricultural productivity and social development (Yang & Sun, 2024).

Network Quality and Performance Factors

The success of digital agriculture initiatives depends on the quality and functionality of mobile networks, which shape smallholder farmers' access to vital information and services (Coggins et al., 2021). Poor network infrastructure, including inconsistent coverage and slow speeds, hampers the use of digital tools and applications to improve agricultural practices (Mazwane et al., 2022). It is especially important to embed digital transformation goals in land reform programmes, which may not explicitly target these applications but have significant potential to fill digital gaps in agriculture (Mazwane et al., 2022). A national digital transformation strategy that fosters interdepartmental cooperation and simplifies regulatory frameworks is vital to address these issues and ensure fair access to digital resources for all farmers (Boikanyo, 2025). Addressing disparities caused by private ICT investments—often favouring large-scale commercial agriculture over smallholder farms—requires comprehensive solutions (Mazwane et al., 2022). Understanding farmers' awareness, perceptions, and challenges—particularly smallholders with limited experience of digital tools—is essential for the effective integration of digital technology in agriculture (Bontsa et al., 2023, 2024). Research shows that many smallholder farmers struggle to use digital technology (Bontsa et al., 2024). Farmers' unfamiliarity with usability often leads them to prefer simpler, low-tech digital solutions that are easier to handle (Bontsa et al., 2023). Despite widespread mobile phone use, Zimbabwean farmers mainly rely on SMS and WhatsApp for agricultural information (Hove et al., 2024). This reliance on key digital technologies underscores the need for user-friendly, locally relevant digital advisory services

that align with farmers' technological skills and preferences (Hove et al., 2024). These platforms should utilise WhatsApp to deliver localised, actionable agricultural advice to boost productivity (Hove et al., 2024). Linking these services with government advisory programmes and developing a centralised e-commerce system could enhance smallholder market access and information sharing (Briones et al., 2023). Such initiatives would help bridge the digital divide and bolster the resilience and sustainability of agriculture in Southern Africa (Briones et al., 2023).

Despite increased mobile device usage, many digital technologies fail globally, including in Southern Africa where smallholder farmers often use outdated practices (Bontsa et al., 2024). Traditional methods and socioeconomic factors shaping farmers' views underscore the need for affordable digital solutions that incorporate indigenous knowledge systems (Bontsa et al., 2023). Customising these technologies to local contexts and practices can improve acceptance and effectiveness within these communities (Bontsa et al., 2023). Additionally, addressing the digital literacy gap is crucial, as many smallholders lack basic skills and knowledge to operate digital technologies (Abdulai, 2022; Olorunfemi et al., 2024). Enhancing digital literacy through targeted training programmes for smallholder farmers is vital to increase adoption and fully unlock the benefits of agricultural digitisation (Magesa et al., 2023). Such training should cover the use of digital devices and applications, as well as critical thinking skills for evaluating online content (Olorunfemi et al., 2024).

The Impact of Coverage Gaps on Socioeconomic Progress

Coverage gaps, particularly in rural and disadvantaged areas, restrict access to essential digital services such as agricultural advice and market information, deepening socioeconomic inequalities. These restrictions hamper economic growth and social inclusion (Hove et al., 2024; Maltitz, 2024). Smallholder farmers are especially affected, as they cannot use digital technology to boost production or access competitive markets, marginalising them within agriculture (Choruma et al., 2024; Olorunfemi, 2024). Compared with larger commercial farms, few small farms have access to 3G or 4G networks (Mehrabi et al., 2020). Disparities in network access worsen food insecurity and limit smallholder farmers' capacity to adapt to climate change by preventing the use of digital tools that could improve resilience (Alant & Bakare, 2021). In developing countries such as those in Southern Africa, food security remains critical amid population growth and environmental challenges, yet widespread digital exclusion hampers progress (Gumbi et al., 2023). In rural South Africa, download speeds are 14.4% lower than in urban areas, and upload speeds are 29.2% lower, reducing the efficiency of data-intensive agricultural applications for smallholder farmers.

The digital divide, caused by poor connectivity and limited digital literacy, lowers agricultural productivity, access to educational resources, and public services, thereby maintaining underdevelopment (Choruma et al., 2024; Mwansa, 2025). Insufficient infrastructure investment and high costs for data and smart devices further exclude rural and impoverished populations from participating in the digital economy (Kamutuezu et al., 2021; Mwansa, 2025). This gap prevents students from accessing online education and small business owners and farmers from utilising e-commerce and digital banking (Mwansa et al., 2025). Digital exclusion hinders technological adoption, especially in rural areas with poor infrastructure and physical remoteness (Mwansa et al., 2025). Rural South African provinces

such as the Eastern Cape face similar ICT access challenges (Mwansa et al., 2025). Limited digital literacy and high costs restrict the adoption and effective use of digital tools by a large portion of the population (Mwansa et al., 2025). These barriers limit the use of information and communication technology to improve agriculture, particularly for smallholder farmers who could gain from market information and meteorological services (Makaula, 2021).

The lack of digital inclusion exacerbates socioeconomic inequality because internet infrastructure is concentrated in cities, benefiting wealthier and more educated groups (Oladunjoye& Chaka, 2025). South Africa is unique in that many smartphone users spend a large part of their salary on data, making reliable internet connection difficult (Alfonsi et al., 2024). Economic barriers limited digital skills, and inadequate technological infrastructure in rural areas hinder the effective use of digital technologies in farming, thereby slowing food self-sufficiency (Aja et al., 2024; Sibiya, 2025). To bridge the digital gap and enable rural communities, especially smallholder farmers, to benefit from digital technologies for sustainable agriculture, improvements in infrastructure, digital literacy, and affordability are essential (Molala & Makhubele, 2021; Mwansa et al., 2025). Success in sectors such as agriculture, education, and healthcare depends on digital inclusion, including access to high-speed internet and digital skills (Aruleba& Jere, 2022). Due to geographic isolation and high costs of devices and data, many Southern Africans, particularly in rural areas, continue to face barriers to digital access (Aruleba& Jere, 2022; Mwansa et al., 2025). In 2020, Sub-Saharan Africa had the lowest internet access rate at 30.04%, compared to North America's 91.52%, slowing digital progress and economic development (Abdulai et al., 2023). In 2018, Southern Africa had 88 mobile phones per 100 people in the SADC region, but this figure often conceals significant disparities in internet access and smartphone ownership, especially among lower-income groups (Baumüller & Kah, 2019).

The lack of suitable digital technology, infrastructure, and connectivity hampers smallholder farmers' integration into digital agricultural ecosystems (Gumbi et al., 2023). Farmers desire interactive digital extension services, yet internet access, centralised information systems, and ICT training are absent (Sen et al., 2025). Many rural farmers do not have formal banking access, which makes it difficult for them to obtain funds or invest in productivity-enhancing resources (Chinelo & Ayodeji, 2022; Fausiyat, 2025).

Device Skills and User Engagement

The lack of affordable, reliable digital devices and digital literacy in rural communities deepens the digital divide, impeding meaningful engagement with agricultural technologies (Astuti et al., 2024; Liu & Zhou, 2023; Zhang, 2025). Rural women struggle to acquire digital skills and use online platforms, perpetuating a gender gap in digital inclusion (Sufian et al., 2023). Despite initial efforts to use digital technologies for agricultural information, sales, and marketing, smallholder farmers' limited digital literacy and skills hinder adoption (Gumbi et al., 2023). Gaps in digital literacy and financial constraints create a cycle that deprives smallholder farmers of vital digital solutions and sustains inequalities (Gumbi et al., 2023; Kibinda, 2025). High device and data costs, poor network infrastructure, and inefficiencies in agricultural institutions limit farmers' ability to use digital advisory services effectively (Coggins et al., 2021; Hove et al., 2024). These barriers reduce productivity and market access and hinder the full integration of digital agriculture, also known as smart

farming or Agriculture 4.0, which is vital for food security and livelihoods in developing countries. The absence of digital ecosystems in many areas limits access to digital solutions for smallholder farmers' problems (Gumbi et al., 2023; Ngulube, 2025). To unlock the transformative potential of digital agro-advisory tools, it is essential to invest in digital infrastructure, enhance digital literacy, and promote stakeholder collaboration (Ofosu-Ampong et al., 2025). This involves developing accessible digital tools that consider smallholder farmers' socio-economic realities and specific needs, rather than applying a standard approach to agricultural technology (Thaher et al., 2025). Due to inadequate infrastructure and difficulty understanding information, many farmers struggle to use digital tools (Olorunfemi et al., 2024).

Information asymmetry limits farmers' access to market data and agricultural knowledge, making it harder for them to utilise transformative inputs such as ICT and mobile internet to increase yields (Kansiime et al., 2021; Khan et al., 2024). To tackle these pervasive issues, contextually suitable and affordable digital solutions, together with extensive digital literacy programmes, are essential to ensure that smallholder farmers have equal access and can use them effectively (Abdulai et al., 2023). The slow uptake of digital agriculture in low- and middle-income countries underscores the need for comprehensive policies to address infrastructure, financial, and skill shortages (Manzoor et al., 2025). These solutions must account for smallholder farmers' specific challenges, including limited access to content, comprehension difficulties, and trust issues (Thaher et al., 2025). The absence of supportive government laws and regulations, together with the high-quality data required for realistic modelling, hinders the widespread adoption of innovative agricultural technologies (Vijayakumar et al., 2025). This situation underscores the importance of investing in knowledge, skills, and inclusive discourse to develop effective initiatives for the adoption of digital agriculture (Thaher et al., 2025).

A comprehensive plan that includes digital literacy training and infrastructure improvements for smallholder farmers is essential to address these issues (Choruma et al., 2024; Herawati, 2023). This requires cost-effective, innovative, and knowledge-based solutions that are accessible and specificallydesigned for small and marginal farmers (Satpathy, 2022). For smallholder farmers to utilise digital tools and services, they must overcome digital literacy challenges and costs (Ninsiima et al., 2025; Oklikah, 2023). Many smallholder farmers struggle to understand digital information or find resources confusing, with some useful tools unavailable due to subscription fees or language barriers (Thaher et al., 2025).

Research Methodology

A rigorous analytical approach is employed to evaluate Southern Africa's intricate mobile connectivity infrastructure, network quality, coverage, and device capabilities. This strategy employed the conceptual analysis method to explore the technology landscape and its influence on digital agriculture in the region (Choruma et al., 2024; Thaher, 2025). The study investigates how mobile service accessibility and quality affect smallholder farmers' adoption and utilisation of digital tools, considering geographical disparities and socio-economic factors (Bontsa et al., 2023; Magesa, 2023). This facilitates a comprehensive analysis of how mobile connectivity, network quality, and device capabilities affect the

adoption of digital agriculture, highlighting policy and technological gaps (Glavanits& Szabó, 2024). The study will evaluate smallholder farmers' attitudes and awareness regarding these technologies, recognising that past experiences and future expectations significantly shape uptake (Bontsa et al., 2024). To establish a robust theoretical framework and identify research gaps, current literature, including scholarly articles, industry reports, and policy papers, were reviewed. Existing frameworks (Geng et al., 2024; Munthali, 2021) points to the use of conceptual analysis methods to explore both the extent of technology adoption and its underlying mechanisms.

Research Results

The results show that infrastructure, network quality, coverage, and device capacity affect uptake and success of digital advice services for downstream technologies and societal development in Southern Africa (Choruma et al., 2024; Ogunsola, 2024). To accurately reflect this complex situation, careful district selection and stratified random sampling of farmers by age, land size, and agricultural practices would be essential for future research (Hove et al., 2024). The study investigated digital agricultural and extension services and found that technology adoption is hindered by obstacles, emphasising the need for customised training programmes that integrate local knowledge systems with digital technologies as an example (Makapela et al., 2025). These programmes should enhance digital literacy and critical thinking, helping farmers distinguish between trustworthy and unreliable digital information to support sustainable agricultural growth (Makapela et al., 2025).

In Zimbabwe, digital technologies have been integrated into extension services, yet issues with network quality and device costs persist, underscoring the need for infrastructure improvements (Hove et al., 2024). Development practitioners recognise logistical and operational barriers to the effective adoption and sustained use of digital advising systems, particularly in remote agricultural regions (Hove et al., 2024). These challenges include poor internet connectivity, limited digital literacy among farmers, and infrastructural constraints (Choruma et al., 2024). A lack of digital literacy among agricultural advisers, who guide farmers, remains a significant obstacle to the widespread adoption of digital solutions in South Africa (Maltitz et al., 2024). Insufficient digital skills among intermediaries hinder smallholder farmers' ability to acquire knowledge and utilise digital agricultural technologies (Bontsa et al., 2023). Research shows that many smallholder farmers are unaware of digital technologies and find them difficult to use, highlighting the need for improved awareness campaigns and training programmes (Bontsa et al., 2024). This underscores the importance of personalised training in digital tools and apps to help farmers incorporate these technologies into their farming practices (Olorunfemi et al., 2024).

Strategic investments in digital platforms to promote sustainable agriculture are feasible given farmers' growing awareness and use of interactive digital extension services (Sen et al., 2025). Rising interest in digitalisation and its benefits—such as improved market access and more informed decision-making—make digital platforms essential for enhancing smallholder farmers' livelihoods and agricultural development in Sub-Saharan Africa. From now until 2026, the use of digital agricultural technology is expected to boost South Africa's economy, particularly in agriculture (Olorunfemi et al., 2024). However, farmers' reluctance to adopt new techniques, aversion to service costs, and limited rural infrastructure continue

to hinder the widespread adoption of digital agriculture (Abdulai, 2022; Hove et al., 2024). These challenges emphasise the need for targeted technological and socio-economic measures to maximise the benefits of digital agriculture in the region. Low digital literacy among smallholder farmers and scepticism towards digital technologies necessitate targeted awareness campaigns and practical training to increase adoption (Abdulai, 2022; Bontsa et al., 2024).

Despite these challenges, research has shifted from small-scale agriculture and extension to innovations, communication technologies, and the dissemination of digital tools (Bontsa et al., 2023). This shift recognises digitalisation's revolutionary potential in agriculture, particularly data-driven technologies that improve farming methods and production (Mazwane et al., 2024; Niksaz, 2025). Given the variety of available technologies, recent research has examined how ICT might enhance productivity (Bontsa et al., 2023). E-commerce platforms are becoming vital for smallholder farmers' market access and information sharing; therefore, assessing their impact on sustainable agriculture is important (Morepje et al., 2024). Addressing digital literacy, infrastructure, and pricing issues that restrict adoption is essential to maximise these platforms' potential (Choruma et al., 2024; Gumbi et al., 2023). Digital technologies in agriculture require robust policy frameworks that enable data interoperability and governance, supporting innovation and private-sector engagement (Mazwane et al., 2022).

Southern Africa Mobile Infrastructure Status

Despite the widespread adoption of mobile connections, network quality and coverage vary, especially in rural areas (Muromba et al., 2025). Inequitable distribution creates a digital gap that prevents many farmers from using decision support systems and online marketplaces (Briones et al., 2023; Mhlanga & Ndhlovu, 2023). Digitalisation has the potential to transform access to and production of information, yet in 2020, only 30.04% of Sub-Saharan Africa had internet connectivity, significantly lower than in other regions (Abdulai et al., 2023). Underdeveloped smallholder farmers in developing countries have limited access to new technology and digital tools, which diminishes agricultural efficiency and food security (Olorunfemi et al., 2024). Digital technology in agriculture can contribute to achieving Sustainable Development Goal nine, but policy constraints and solutions often remain unclear (Mazwane et al., 2022). A lack of understanding frequently impedes efforts to reduce information asymmetries, which restrict rural farmers' access to market information, loans, and essential agricultural services (Khan et al., 2024). Furthermore, poor network coverage in rural Malawi and unreliable electricity supply in Tanzania hinder the use of mobile phones for disseminating agricultural information (Makaula, 2021).

Infrastructural issues, high data costs, and low device affordability exacerbate digital inequalities, preventing small-scale food producers from using ICTs toimproveagriculture (Alfonsi et al., 2024; Hove, 2024). Despite their long-term benefits, budget constraints and the perceived costs of digital technologies hinder the widespread adoption of innovative agricultural practices (Manzoor et al., 2025). Only 24–37% of farms under 1 hectare have 3G or 4G coverage, compared to 74–80% for farms over 200 hectares (Mehrabi et al., 2020). Unequal access to vital digital infrastructure limits smallholder farmers' ability to participate in and benefit from the digital revolution in agriculture (Panwar & Sahoo, 2025; Zhang et al., 2025). Climate change, financial shortages, and agricultural restrictions further impede the

integration of digital solutions (Gumbi et al., 2023). Digital agriculture can address the complex problems faced by smallholder farmers, but insufficient or absent digital ecosystems restrict its potential (Gumbi et al., 2023). This highlights the urgent need for targeted interventions to improve infrastructure and establish a comprehensive digital ecosystem, including digital literacy programmes and policy frameworks that promote equitable access and adoption of these technologies by smallholder farmers (Gumbi et al., 2023; Mhlanga & Ndhlovu, 2023).

Governments, the private sector, and civil society must work together to develop sustainable digital solutions for Southern African agricultural communities (Fausiyat, 2025; Kansiime et al., 2021). To promote inclusivity and sustainability, collaborations should take into account local people's digital skills and communal practises, focusing on cost-effective solutions (Paget et al., 2025). The divide in South African agriculture, emphasised by historical land dispossessions, causes uneven adoption of digital technology between large-scale commercial farms and smallholder businesses (Mazwane et al., 2022). This gap shows how land reform can help address agricultural inequalities and foster digital transformation (Mazwane et al., 2022). To close these systemic gaps, strong, inclusive digital infrastructure and policies that ensure fair access to land, financial resources, and digital literacy training are necessary (Choruma et al., 2024; Yang & Sun, 2024). These issues are intensified by rural areas' limited access to, and high costs of, digital infrastructure and the lack of digital skills among agricultural communities (Aruleba& Jere, 2022). Tackling these challenges requires a coordinated effort to improve digital literacy and deliver specialised training, especially in remote regions (Choruma et al., 2024). This will empower smallholder farmers to utilise digital technologies more effectively, increasing agricultural productivity and supporting sustainable development in Southern Africa (Abdulai et al., 2023; Kitole, 2023). Such initiatives should prioritise affordable, accessible, and straightforward technologies like community radio and mobile phones for spreading knowledge, given that infrastructure and literacy issues hinder IoT and AI adoption (Ngulube, 2025). This comprehensive approach, combining infrastructure improvements with capacity-building, is vital for regional food security and agricultural progress (Gumbi et al., 2023). Digital platforms, integrated with agricultural extension services, can bridge the information gap by providing personalised support and resources that respect local knowledge and address structural challenges (Mugari et al., 2025).

Network Quality Metric Evaluation

A comprehensive network quality assessment is vital for understanding mobile connection performance and accessibility across Southern Africa, particularly for agricultural applications. Rural farmers rely on digital advisory services and mobile financial tools, yet signal strength, latency, and data transfer speeds determine their effectiveness (Fausiyat, 2025; Hove et al., 2024). These factors vary across Southern Africa's diverse terrain, complicating digital service delivery and requiring substantial infrastructure investment (Don, 2025). Beyond technical specifications, user experience should also encompass network reliability, cost-effectiveness, and access to support services—especially for those with limited digital literacy (Oklikah et al., 2023). Consequently, although mobile network operators emphasise extensive coverage, poor signal quality and inconsistent connections in many rural areas hinder digital inclusion (Hove et al., 2024). The gap between advertised coverage and actual performance underscores the need for comprehensive network quality

assessments that genuinely reflect user experiences in underserved regions (Sharma &Shivandu, 2024). While 5G networks offer high data rates and low latency, rural areas remain underserved, despite their vital role in agriculture, including microclimate monitoring and pest detection (Ramírez-Arroyo et al., 2024). Smallholder farmers are especially affected by the digital divide, which restricts their ability to leverage technology for production and market access (Choruma et al., 2024; Hove, 2024). Advances in connectivity enable real-time data analysis for precision agriculture, enhancing crop yields and livestock management (Farinha & Martins, 2025; Ramírez-Arroyo et al., 2025). However, inadequate network infrastructure in rural areas hampers the effective use of these technologies, resulting in unstable performance and limited scalability (Adarsh et al., 2021). Modern cellular networks, such as 4G, are often hampered by slow, unreliable connections and high data costs, particularly in rural sub-Saharan Africa (Choruma et al., 2024; Shetye, 2022).

The disparity is exacerbated by the inadequacy of current terrestrial broadband technologies in rural areas, where fibre-optic installation is often prohibitively expensive and satellite communication has higher latency and lower capacity than 5G (Islam et al., 2025). Urban areas enjoy many reliable connectivity options, whereas rural regions face limited internet access, slower data speeds, inconsistent connections, and restricted data allowances (Marshall et al., 2020; Zhang et al., 2021). Rural South Africa experiences 14.4% slower download speeds and 29.2% slower upload speeds compared to urban centres (Mwansa et al., 2025). This disconnect hampers data-driven agricultural practices like precision farming and real-time livestock monitoring, which depend on dependable, fast connectivity (Ramírez-Arroyo et al., 2024). Due to unreliable energy and internet access on farms in Southern Africa, specialised IoT solutions that operate independently of standard, often costly, Wi-Fi or cellular networks are typically required (Effah et al., 2024). Innovative, low-energy, self-sustaining connection solutions for remote farms are necessary to facilitate real-time data exchange and enhance operational efficiency (Ngulube, 2025). A comprehensive approach, combining terrestrial 5G and satellite networks, is vital to meet network availability needs for precision agriculture and livestock surveillance in distant rural regions (Ramírez-Arroyo et al., 2025).

Integrated methods surpass terrestrial infrastructure limitations, offering extensive coverage for vital agricultural applications (López et al., 2023; Ramírez-Arroyo et al., 2024, 2025). 5G technology holds great potential to revitalise rural areas in agriculture, healthcare, and education, but infrastructure and deployment costs remain barriers (Farinha & Martins, 2025). Although challenging, integrating non-terrestrial networks like satellites is essential for expanding coverage to rural agricultural regions where conventional cellular networks are uneconomical (Ramírez-Arroyo et al., 2024, 2025).

Analysis of Mobile Coverage disparities

Mobile coverage disparities in Southern Africa hinder efforts to bridge the digital divide, particularly for rural and underprivileged populations (Mwansa et al., 2025). Low population density and long distances make traditional network deployment uneconomical (Shahid et al., 2024). To deliver extensive and reliable connectivity, innovative, cost-effective solutions are needed, such as the strategic use of satellites and UAVs (Plastras et al., 2023). Hybrid techniques enable remote agricultural areas to participate in the digital economy and utilise

digital innovations (Cabrera-Castellanos et al., 2021; Homssi& Al-Hourani, 2021). The move towards 6G technology emphasises sustainability and social impact, notably rural wireless access, as key research and standardisation priorities (Chaoub et al., 2021). Satellite systems will facilitate 5G and 6G in remote and rural zones inaccessible to terrestrial networks, enhancing resilience and spectrum efficiency through terrestrial-non-terrestrial integration (Höyhtyä et al., 2024). Advanced hybrid networks, blending terrestrial and non-terrestrial elements, enable ubiquitous connectivity in agricultural settings, supporting autonomous agri-robotics and other agricultural technologies that require dependable communication beyond 4G or Wi-Fi 6 systems in remote locations (Zhivkov & Sklar, 2023).

To improve broadband coverage in rural and remote areas, High-Altitude Platform Stations and Low Earth Orbit satellites should be explored (Cabrera-Castellanos et al., 2021; Nguyen et al., 2024). Achieving comprehensive connectivity in these regions requires artificial intelligence to integrate spatial, aerial, and terrestrial networks for enhanced performance and coverage (Fourati et al., 2022). In rural areas, high infrastructure costs and limited cell site revenue make traditional telecom investments less appealing (Fourati et al., 2022). This challenge highlights the transformative potential of Non-Terrestrial Networks, including drones and satellites, to deliver broadband connectivity to underserved rural communities at a lower cost (Fang et al., 2021; Zhang et al., 2021).

Sustainable development and socio-economic progress in these regions will require the deliberate integration of diverse network technologies to bridge the digital divide (Chaoub et al., 2021). The Internet of Remote Things, which extends IoT to remote areas without terrestrial or cellular networks, employs non-terrestrial methods to overcome connectivity challenges (Plastras et al., 2024). This shift towards integrated terrestrial and non-terrestrial networks is crucial for the 6G era, which emphasises ubiquitous connectivity and reliable performance across various geographical terrains, including remote locations (Chaoub et al., 2021; Nguyen et al., 2024). Achieving this vision necessitates advanced signal processing, edge and cloud computing, and Deep Reinforcement Learning for Low Earth Orbit satellites and aerial platforms, particularly AI-driven NTN-IoT implementations (Jamshed et al., 2025). These developments, alongside Next Generation Multiple Access technologies, are transforming global connectivity by establishing more dynamic and resilient communication infrastructures (Jamshed et al., 2025). The inclusion of Non-Terrestrial Networks in 6G standards through 3GPP Releases 17-19 highlights its significance for global connectivity (Jamshed et al., 2025). Satellites and high-altitude platforms work together with terrestrial infrastructure to enhance coverage, especially in remote and underserved areas (Jamshed, Haq, et al., 2025; Jamshed, Kaushik, et al., 2025).

This integration enhances network resilience and expands high-speed internet access in large, sparsely populated areas (Azari et al., 2022). To enable ubiquitous 6G connectivity, this model employs AI algorithms to address task offloading and network routing challenges in integrating non-terrestrial networks with terrestrial networks (Mahboob & Liu, 2024; Nguyen et al., 2024). AI and machine learning boost network efficiency and reliability by optimising resource allocation, spectrum management, and predictive maintenance in integrated NTN-TN systems (Baena et al., 2025; Jamshed, 2025). Despite propagation delays and complex beam management, NTNs' extensive coverage and scalability make them suitable for next-generation communication systems (Mahboob & Liu, 2024; Nguyen et al.,

2024). However, the complete integration of NTNs and terrestrial networks remains in early stages, with current 3GPP releases providing vital guidelines for their coexistence and interoperability (Jamshed et al., 2025). The ITU Radiocommunication Sector's International Mobile Telecommunications-2030 framework highlights the role of NTNs in delivering intelligent, seamless connectivity for reliable, sustainable, and resilient communications within the 6G ecosystem (Jamshed et al., 2025).

These advances demonstrate a clear trend towards more cohesive and intelligent networks, where AI-driven optimisation is essential to solving problems in hybrid terrestrial and non-terrestrial systems. Complex predictive algorithms and real-time decision-making using large language models are being explored to optimise data flow, signal processing, and network management for 5G/6G communication (Javaid et al., 2024). Given their spatiotemporal dynamics and significant interdependencies, coupled communication- and computing-embedded space-air-ground integrated networks require this integration to address complex resource allocation challenges (Chen et al., 2024). Hierarchical deep reinforcement learning improves spectrum sharing and interference management in multi-tier, heterogeneous integrated terrestrial and non-terrestrial networks (Umer et al., 2025). This robotics-inspired approach indicates that large language models can manage these complexities (Shokrnezhad& Taleb, 2025). Large Language Models and Generalised Pretrained Transformers will facilitate intent recognition and autonomous operation in 6G systems, transforming network functionality (Ali et al., 2023; Tarkoma, 2023).

Wireless network resource allocation, interference control, and orchestration will evolve with AI-native generations (Abdallah et al., 2024). A cohesive, data-driven adaptation layer using a single large language model trained on radio, optical, and acoustic data can effectively address Channel State Information ageing and bandwidth discrepancies in space-air-ground-sea communication frameworks (Yang et al., 2025). This technique projects different inputs into a token space, enabling a single backbone for the Space-Air-Ground-Sea Integrated Network's four layers (Yang et al., 2025). Intent-driven networks can automate 6G's diverse and dynamic systems by translating high-level objectives into optimisation rules (Habib et al., 2025). Using large language models in wireless network orchestration is uncharted, but their advanced natural language understanding capabilities for autonomous control could assist in managing and optimising next-generation networks (Abdallah et al., 2024; Shokrnezhad& Taleb, 2025).

Device Penetration and Capabilities Assessment

Understanding mobile device adoption and functionality is essential for assessing Southern African markets' readiness for advanced mobile connections. This review examines smartphone adoption rates, the prevalence of feature phones, and device technical features,including CPU speed, RAM, and advanced cellular compatibility. The study also investigates the widespread use of artificial intelligence at the device level, including on-device AI for processing and privacy, as well as edge and cloud AI for more sophisticated computing (Li et al., 2025). On-device AI capabilities, often driven by dedicated neural processing units, enhance user experience by boosting application performance, improving camera functions, personalising services, and refining network communication infrastructure (Abel et al., 2025).

The ability of these devices to support and integrate with future technologies, especially advanced 5G and emerging 6G concepts, will determine how quickly these regions adopt and benefit from mobile communication innovations (Sevim et al., 2024). This involves testing their compatibility with integrated satellite, aerial, and terrestrial networks, which are increasingly essential for seamless communication across diverse terrains (Javaid et al., 2024). To maintain national or operator-level control over AI development and deployment, AI-native 6G architectures must prioritise local data processing and sovereign AI solutions (Chetty et al., 2025). Mobile ecosystems become more resilient and efficient with decentralised processing and AI-driven network management (Karapantelakis et al., 2024; Li et al., 2025). The expansion of mobile AI within devices by technology firms highlights a vital convergence that is shaping communication futures (Goggin, 2025). The deployment of generative AI models on edge devices in low-cost, commercially accessible components—often used for rural connectivity—must undergo thorough evaluation (Nezami et al., 2024; Wang et al., 2025). Over 80% of people in least developed nations use mobile phones, yet a significant percentage lack internet access, underscoring the importance of resilient, on-device AI functions that can operate independently of network connectivity (Yang et al., 2024).

The computational, memory, connectivity, and energy constraints of deploying advanced generative AI models on mobile and edge devices in these contexts must be addressed (Sai et al., 2024; Zhang et al., 2025). Local data processing reduces frequent, substantial data transfers to cloud servers, lowering communication overhead and optimising resource use for AI models in mobile contexts (Zhang et al., 2024). This is particularly important in bandwidth-constrained regions, such as rural areas, where cloud-based AI inference or model updates are impracticable (Zhang et al., 2024). Therefore, model compression and algorithmic efficiency are essential for generative AI to function effectively in low-resource settings, such as Southern Africa (Vuruma et al., 2024). This challenge underscores the need for scalable, efficient generative AI models that can run on-device to overcome infrastructural limitations and enhance digital inclusion in the region (Sai et al., 2024). Sovereign AI enables national or operator-level governance of AI development, deployment, and lifecycle management, particularly for xApps and rApps under O-RAN frameworks (Chetty et al., 2025). Southern African nations require this strategic approach to foster local innovation, protect data sovereignty, and develop AI solutions tailored to their socio-economic and infrastructural contexts (Bariah et al., 2024; Li et al., 2024). It addresses issues of data sovereignty, security, and regulatory compliance by training, deploying, and managing AI models locally, thereby promoting self-reliance and technological autonomy (Chetty et al., 2025). Localised control enables culturally sensitive and contextually relevant AI applications, particularly those targeting unique challenges in remote healthcare, agriculture, and education (O'Neill et al., 2024; Vuruma, 2024).

Generative AI models in mobile edge networks introduce a new paradigm that can enhance network intelligence and deliver numerous benefits. Positioning models closer to end-users reduces reliance on cloud infrastructure for computation (Lai et al., 2024). This shift is crucial for meeting 6G network latency requirements and supporting real-time mobile AI generation (Lai et al., 2023). Moreover, it enables deeper AI integration, laying the foundation for reliable AI principles across networks and devices (Çelik &Eltawil, 2024). Advances in distributional generative AI are essential for achieving global ambient

intelligence, particularly in 6G networks that require real-time perception, reasoning, and actions aligned with human behaviour and mobility patterns (Mohsin et al., 2025). AI, particularly generative AI, is expected to become a core component of 6G network architecture (Li et al., 2025). This necessitates a redesign of network architecture and the adoption of AI-native frameworks to facilitate extensive AI integration and real-time processing (Chetty et al., 2025). AI is used to coordinate network functions, optimise resource allocation, and deliver personalised edge services (Navaie, 2024). A decentralised AI ecosystem will shift processing from data centres to edge devices, enhancing AI application customisation and resilience (Nezami et al., 2024). This paradigm shift moves AI algorithm processing from centralised cloud infrastructure to distributed edge devices, supporting more real-time and context-aware applications (Li et al., 2025; Nezami, 2024). Local processing enables users to utilise generative AI or multimodal LLM functions, such as image creation or enhancement, in real time, regardless of network conditions (Zhang et al., 2024). This decentralised AI architecture is vital for 6G networks, which will evolve from an Internet-of-everything to an Internet-of-intelligence through hybrid heterogeneous networks where generative AI models leverage insights from numerous connected end devices to provide advanced network solutions (Chen et al., 2024). Generative AI and 6G networks will allow GAI to learn from personalised data across multiple interconnected 6G devices (Chen et al., 2024). Distributed AI-as-a-service frameworks must dynamically allocate training and inference workloads among cloud, fog, and edge resources to optimise performance and resource use in 6G environments (Janbi et al., 2020). In "GAI-native networks," generative AI is embedded within 6G architecture to establish a closed-loop knowledge flow, enhancing network capabilities and service quality (Chen et al., 2024).

Coordinating distributed generative AI models across cloud, edge, and device layers fosters continuous learning and model optimisation through bidirectional knowledge exchange (Chen et al., 2024; Zhong, 2024). This architecture enables pre-trained cloud-based generative AI models to instruct edge models, which gather personalised data to enhance the network (Chen et al., 2024; Zhong, 2024). This integrated communication and computing technology increases service capacity by 98% over 5G multi-access edge computing (Yang et al., 2025). It also meets the rising demand for real-time interactions with generative AI services, which traditional 5G latency can sometimes limit (Lai et al., 2023; Yang, 2025). Embedding AI capabilities directly into Radio Access Network nodes allows for collaborative bandwidth and computational resource management, improving AI application performance (Yang et al., 2025). Compared to standard 5G MEC implementations, this integrated approach reduces end-to-end task latency by 60%, enhances service capacity by 60%, and decreases operational computing costs by 27% (Yang et al., 2025)

Discussion

Mobile connectivity in Southern Africa is complex, influenced by factors such as infrastructure development, network quality, coverage, and device capabilities. This analysis applies digital divide and ICT accessibility theories to examine how these factors shape digital inclusion, economic growth, and the broader socio-economic context (Aruleba& Jere, 2022; Kuteesa et al., 2024). Efforts by mobile network operators to improve communication infrastructure in rural areas have often fallen short of expectations, mainly because many people cannot afford digital services, as extensive research shows (Rey-Moreno, 2015). Even where infrastructure is sufficient, widespread gaps in digital literacy and the lack of locally

relevant information prevent effective use and adoption of digital technologies (Ahiaku et al., 2025; Okonkwo, 2025). Persistent disparities in access to digital technology in impoverished nations threaten to worsen inequalities unless addressed inclusively (Ehimuan et al., 2024; Kibinda, 2025). The digital divide, caused by unequal access to and use of information and communication technology, continues to impede socioeconomic progress, especially in emerging economies where additional barriers exacerbate existing inequalities (Lambrechts & Sinha, 2019). Budget constraints, digital illiteracy, and low smartphone ownership among rural populations hinder the development of digital infrastructure that could foster economic growth and sustainable livelihoods (Gigaba et al., 2025). Rural areas often suffer from unreliable digital infrastructure and limited digital literacy, restricting the deployment of digital solutions that could otherwise enhance economic development. Internet connectivity often relies on the electrical grid, which in South Africa is frequently unreliable, necessitating further infrastructure investments to achieve digital inclusion (Modiba & Kaye, 2023, p. 23).

Due to low profitability, Mobile Network Operators sometimes avoid investing in network infrastructure in remote or challenging rural areas because of high installation and operational costs (Kibinda et al., 2025). This reluctance fosters digital exclusion, as many low-income individuals, particularly in rural regions, lack internet access (Zhang et al., 2025). Therefore, innovative public-private policies and partnerships that promote infrastructure development in underserved areas while addressing affordability and digital literacy are necessary to bridge this divide (Oladunjoye& Chaka, 2025, p. 659; Selemela et al., 2023, p. 246). These initiatives must also address the shortage of digital skills training, which impedes the development of essential digital capabilities and reduces awareness of their benefits (Aruleba& Jere, 2022). This recurring issue highlights the need for comprehensive strategies that confront infrastructure and socio-economic barriers, enabling marginalised communities to participate digitally (P., 2025; Xiao et al., 2024). To combat digital technology inequalities, targeted subsidies, rural broadband projects, and digital literacy programmes are crucial (Djatmiko et al., 2025; Giest, 2025). Strategic investments in digital infrastructure, such as solar-powered digital hubs and rural internet, have improved digital literacy and inclusion in remote developing nations (Dosumu, 2024). Digital skills empower individuals and communities by creating economic opportunities, thereby alleviating poverty (Aruleba& Jere, 2022). To maximise these benefits, digital training programmes must be developed in parallel, enabling communities to utilise existing ICT infrastructure, especially in areas where digital access is not yet regarded as essential (Aruleba& Jere, 2022).

Policy measures aim to improve digital literacy and provide affordable, accessible digital technologies, fostering a culture where technology is seamlessly integrated into everyday life and economic development (Banerjee & Mete, 2024). To enhance digital literacy and connectivity among marginalised groups, successful digital inclusion projects often depend on strong alliances between governments, businesses, and NGOS (Ehimuan et al., 2024). Even in wealthy countries, gaps in urban and rural broadband connectivity persist, reflecting issues seen in Southern Africa and emphasising the global digital divide (Djatmiko et al., 2025). Therefore, it is crucial to carefully analyse effective strategies to bridge this divide, especially those suited to Southern Africa's socio-economic and geographical contexts. This review provides policymakers, researchers, and practitioners with vital insights to develop

more effective, inclusive, and sustainable solutions for a digitally connected world (Ehimuan et al., 2024).

Results of Infrastructure Analysis

Southern Africa, like other developing countries, faces challenges in digital literacy and inclusion due to inadequate infrastructure, including unreliable power supplies and poor internet connectivity (Dosumu, 2024). Addressing these infrastructure issues is crucial for achieving widespread digital adoption and the success of digital literacy initiatives (Evurulobi et al., 2024; Mnkandla & Volk, 2025). Effective strategies must also consider socio-economic, cultural, and technological contexts, which vary widely across Africa, requiring personalised approaches rather than one-size-fits-all solutions (Ehimuan et al., 2024; Evurulobi, 2024). Building resilient literacy systems capable of adapting to the digital transition requires targeted investments in human, technological, and financial skills (Nkomo & Matli, 2023). South African efforts should also aim to close the digital gender gap by empowering women through improved access and digital skills (Mnkandla & Volk, 2025). Unequal access to devices and the internet, especially in rural areas, limits women's use of technology (Mnkandla & Volk, 2025). Insufficient teacher training in ICT integration hampers the adoption of educational technology, particularly in remote schools (Flowers & Tanner, 2024; Mkhonto & Mubangizi, 2024). Low digital literacy among educators perpetuates a cycle that deprives pupils of essential digital skills, intensifying the technological divide (Sasere&Makhasane, 2023, p. 59). This impairs the integration of ICTs into curricula, despite government efforts to procure equipment and offer training (Sasere&Makhasane, 2023). Many educational institutions lack resources and infrastructure, making it difficult for teachers and students to utilise technology (Aricindy et al., 2025). While national policies often prioritise infrastructure development, local challenges arise from shortages and unprepared teachers (Hanifah et al., 2025), leading to varied policy implementation. Insufficient international collaboration and funding, crucial for building and maintaining robust ICT infrastructure in emerging nations, can worsen existing issues (Sasere&Makhasane, 2023). Overcoming digital inequalities in Sub-Saharan Africa is essential to providing equitable access to quality education (Kelly &Rutazihana, 2024). The COVID-19 pandemic has further widened the digital divide.

Network Quality Effects on User Experience and Advancement

User experience and digital service adoption across sectors depend on the quality of network infrastructure. Slow speeds, frequent disconnections, and poor coverage undermine network reliability, hampering economic growth by restricting access to essential online resources and services (Kelly &Rutazihana, 2024). In Sub-Saharan Africa, internet and mobile subscriber rates influence education and socioeconomic progress (Kelly &Rutazihana, 2024). Therefore, improving network reliability and high-speed internet connectivity is essential for digital inclusion and participation in the global digital economy (Kelly &Rutazihana, 2024). In sparsely populated areas with limited 3G and 4G coverage, providers have few incentives to invest in faster networks because security risks and unstable power supplies constrain profitability (Heeks& Bukht, 2018, p. 6). Infrastructure and economic barriers widen the digital divide, making it harder to enhance connectivity and digital literacy across the continent (Doerksen et al., 2024; Yalla, 2025). Digital transformation is sometimes hindered by weak regulatory frameworks and inadequate ICT infrastructure investment, especially in higher education within developing countries

(Ntorukiri et al., 2022). Unresolved social and economic challenges complicate the development of comprehensive ICT strategies (Ntorukiri et al., 2022). This neglect leads to significant disparities in network quality, which negatively impact educational delivery and foster a new form of digital inequality based on high-quality internet access rather than mere connectivity.

Infrastructural issues, socio-economic barriers, and low digital literacy hinder access to AI-enhanced educational resources and widen the digital divide for marginalised groups (Mustafa, 2025; Vesna, 2025). Without tackling these core inequalities, AI in education could deepen disparities and marginalise educators lacking digital and AI skills (Dlamini & Ndzinisa, 2025). For AI initiatives to be culturally relevant, accessible, and supported by robust infrastructure and training, they require a comprehensive review (Adıgüzel et al., 2023; Bali et al., 2024; Mustafa, 2025). This policy concentrates on human development and equitable access for marginalised groups, particularly in the Global South, where biased data and algorithms risk worsening educational inequality (Adıgüzel et al., 2023). It calls for national policies to strengthen digital infrastructure, promotes public-private partnerships for fair technology adoption, and highlights the importance of teacher training centred on AI pedagogy (Mustafa, 2025). To improve teaching standards and student engagement in Ghana, AI programmes must be tailored to their cultural, economic, and infrastructural contexts (Osondu et al., 2024).

Addressing Coverage Gaps and Promoting Digital Inclusion

Digital inclusion requires targeted network expansion into underserved rural and remote areas to guarantee universal, equitable access to high-quality mobile connectivity. Innovative solutions, such as shared infrastructure models and satellite technology, can overcome geographical barriers and reduce deployment costs (Osondu et al., 2024). Government policies should also promote infrastructure development in specific regions through subsidies or public-private partnerships, ensuring that economic viability alone does not drive network expansion. Regulations must foster competition and innovation while offering affordable mobile services to all citizens, regardless of socioeconomic background. This comprehensive approach would enhance coverage, promote digital literacy, and support AI integration, thereby advancing socio-economic development and educational equity (Mustafa, 2025; Osondu et al., 2024). Ghanaian initiatives demonstrate that locally tailored, culturally sensitive AI development ensures that technology interventions are relevant and beneficial within regional educational contexts and challenges (Osondu et al., 2024). Strategic alignment is essential to translate AI's potential into educational benefits and to bridge the digital divide that hampers equitable learning in poorer nations (Vesna, 2025). AI in education demands targeted, context-aware solutions that address challenges such as student engagement, personalisation, and administrative efficiency (Osondu et al., 2024). Implementing local languages, such as Swahili, and enhancing AI literacy involve adapting AI models to diverse linguistic and educational environments (Kondoro, 2025). Furthermore, integrating inclusive AI in education requires teacher training and community efforts to foster digital literacy (Vesna, 2025). Open-source AI educational technologies and platforms enable resource-limited institutions to overcome financial barriers (Vesna, 2025).

These programmes help resource-limited nations integrate AI into healthcare, education, energy, and government without following traditional developmental stages (Frimpong, 2025; Khan et al., 2024). For fair access to AI-enhanced learning resources, developing countries in Southern Africa must address infrastructure challenges, particularly mobile connectivity and network quality (Samuel-Okon & Abejide, 2024). This entails a comprehensive evaluation of mobile infrastructure to identify issues with coverage, network stability, and device costs that impede AI in education (Chisom et al., 2024). The assessment should consider network availability and service quality, including bandwidth and latency, which influence AI application performance (Funda &Mbangeleli, 2024). AI in education across Africa is further hindered by unreliable internet infrastructure and a shortage of qualified educators (Boateng, 2024). To equip educators for AI integration, significant investments in digital infrastructure and extensive teacher training are essential (Mustafa, 2025). Tailored policies must address disparities in connectivity and digital literacy to strengthen infrastructure and promote equity (Saal et al., 2025). This involves fostering public-private partnerships to expand network coverage and subsidise devices and data plans for students and teachers (Novianti, 2025). In regions characterised by socioeconomic inequities and weak regulatory oversight, comprehensive policy frameworks are necessary to tackle ethical issues, data privacy, and algorithmic bias (Abulibdeh et al., 2023; Patel &Ragolane, 2024; Valdivieso & González, 2025). These frameworks must balance innovation and safety to implement AI technology ethically and inclusively (Patel &Ragolane, 2024). This demands a meticulous review of AI's role in customising learning experiences and automating assessments, while addressing infrastructure, educator preparation, and ethical concerns (Mustafa, 2025). Furthermore, these regions must address infrastructure deficits, high implementation costs, educator shortages, and ethical issues related to data privacy and bias to effectively integrate AI into education.

Device Capability Matters for Mobile Connectivity Adoption

Mobile connectivity in Southern Africa is closely tied to the availability and effectiveness of end-user devices, shaping how people use network infrastructure for education and digital participation (Aaron & Mahamod, 2025). This includes affordable, versatile smartphones and other mobile devices capable of supporting AI-driven applications and high-bandwidth content essential for modern education (Elifas&Simuja, 2024). In rural and impoverished areas, outdated, inefficient devices hinder access to advanced AI tools and comprehensive digital learning resources (Haetami, 2025). Growing disparities in device capacity limit many students' access to personalised learning experiences and specialised educational resources (Muringa, 2025). To promote equitable participation in AI-enhanced education, subsidised device programmes or AIED Unplugged technologies—neither of which require stable internet or extensive technical expertise—are necessary (Isotani et al., 2023). To bridge the digital divide, it is vital to ensure AI in education is accessible to all, regardless of socio-economic status or location (Adıgüzel et al., 2023; Al-Zahrani, 2024; Mustafa, 2025). AI has the potential to tackle challenges such as poor educational quality and a significant skills gap among graduates by fostering innovation and industrial growth across Africa (Falebita& Kok, 2024). However, the true potential of AI in education remains underappreciated, with cultural, economic, and infrastructural barriers hindering its broad adoption, especially in Lesotho, Nigeria, and Rwanda (Olayinka et al., 2024). Overcoming these barriers requires careful policy development that accounts for Southern African socio-economic realities and prioritises technological progress and ethical governance (Muringa, 2025).

Growing disparities in device capacity limit many students' access to personalised learning experiences and specialised educational resources (Muringa, 2025). To promote fair participation in AI-enhanced education, subsidised device programmes or AIED Unplugged technologies—requiring neither stable internet nor advanced technical skills—are essential (Isotani et al., 2023). To eliminate the digital divide, it is crucial to ensure that AI in education is accessible to everyone, regardless of socio-economic background or location (Adıgüzel et al., 2023; Al-Zahrani, 2024; Mustafa, 2025). AI has the potential to address challenges such as poor educational quality and a large skills gap among graduates by fostering innovation and industrial development across Africa (Falebita& Kok, 2024).

Policy Recommendations

A comprehensive policy framework that prioritises targeted actions to address infrastructural deficiencies and enhance digital literacy in Southern Africa is essential to tackle these challenges and facilitate AI integration (Saal et al., 2025). This framework should focus on developing durable digital infrastructure, expanding internet access, and providing affordable devices for students and teachers. Policies must also ensure equal access to AI technologies, thereby fostering inclusive educational environments for all learners ratherthanexacerbating socioeconomic inequalities. Considering the socio-economic challenges in the Global South, clear guidelines and policies for the responsible and ethical deployment of AI in education—covering data privacy and algorithmic fairness—are crucial to this framework (Ren & Wu, 2025; Valdivieso & González, 2025). To stay abreast of the rapidly changing AI landscape and its societal impacts, these policies must include ongoing monitoring and review (Mustafa, 2025). Owing to the Western-centric nature of current AI tools, collaborations between academic institutions, industry, and government can help drive innovation in locally relevant AI solutions that are culturally appropriate and tailored to regional educational needs (Boateng, 2024; Elifas&Simuja, 2024). Teachers need training and continuous professional development to incorporate AI into literacy education and maximise its pedagogical potential (Aaron & Mahamod, 2025). To equip educators and learners with AI literacy skills, a comprehensive curricular approach is required—one that enables critical evaluation and ethical use of AI tools (Adıgüzel et al., 2023; Daher, 2025; Funa & Gabay, 2024).

Policy recommendations should focus on national AI programmes aligned with educational goals, emphasising adaptable regulatory frameworks to keep pace with rapid technological innovation (Osondu et al., 2024). AI integration must support sustainable development goals and ensure equitable access to quality education across the region, improving learning environments and outcomes (Daher, 2025). This strategic integration requires careful evaluation of AI's economic costs and benefits, including its potential to foster educational innovation and efficiency (Sands, 2025). Students and educators need AI literacy to critically evaluate, ethically use, and effectively apply AI technologies across various disciplines (Funa & Gabay, 2024). To navigate AI's transformative impacts in education, AI literacy must encompass understanding, assessment, collaboration, contextualisation, independence, and ethics (Allen &Kendeou, 2023). It ensures educators are knowledgeable about implementing AI technologies in their classrooms, embedding AI skills into modern education (Bakhadirov et al., 2024).

References

Aaron, S., &Mahamod, Z. (2025). Artificial Intelligence (AI) Technology in Learning Malay Language Literacy Skills among Students. *International Journal of Research and Innovation in Social Science*, 5982. https://doi.org/10.47772/ijriss.2025.909000486

Abdallah, A., Albaseer, A., Celik, A., Abdallah, M., &Eltawil, A. M. (2024). *NetOrchLLM: Mastering Wireless Network Orchestration with Large Language Models*. https://doi.org/10.48550/ARXIV.2412.10107

Abdulai, A. (2022). Toward digitalization futures in smallholder farming systems in Sub-Sahara Africa: A social practice proposal. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.866331

Abdulai, A., Quarshie, P. T., Duncan, E., & Fraser, E. (2023). Is agricultural digitization a reality among smallholder farmers in Africa? Unpacking farmers' lived realities of engagement with digital tools and services in rural Northern Ghana. *Agriculture & Food Security*, *12*(1). https://doi.org/10.1186/s40066-023-00416-6

Abdullahi, A. I., &Asongu, S. (2021). The asymmetric effect of internet access on economic growth in sub-Saharan Africa. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3967115

Abel, M., Ahmad, I., Casado, C. Á., Berner, R., Bettinelli, M., Björk, K. M., Capobianco, M., Gross, J. J., Nguyen, T., Hui, P., Kostakos, P., Kumar, A., Laakkonen, M.-P., Liu, X., Liu, Z., Nguyen, L., Nguyễn, H. T. L., Ozparlak, B. O., Pietiläinen, V., … Zourmand, A. (2025). *Large Language Models in the 6G-Enabled Computing Continuum: a White Paper*. https://hal.science/hal-04958090

Adarsh, V., Nekrasov, M., Paul, U., Mangla, T., Gupta, A., Vigil-Hayes, M., Zegura, E., & Belding, E. (2021). *Coverage is Not Binary: Quantifying Mobile Broadband Quality in Urban, Rural, and Tribal Contexts*. 1. https://doi.org/10.1109/icccn52240.2021.9522152

Adesiyan, T. (2025). Leveraging Agricultural Credit and Digital Finance for Enhancing Smallholder Productivity and Rural Economic Growth. *International Journal of Research Publication and Reviews*, *6*(8), 642. https://doi.org/10.55248/gengpi.6.0825.3090

Adıgüzel, T., Kaya, M. H., & Cansu, F. K. (2023). Revolutionizing education with AI: Exploring the transformative potential of ChatGPT. *Contemporary Educational Technology*, *15*(3). https://doi.org/10.30935/cedtech/13152

Ahiaku, P. K. A., Uleanya, C., &Muyambi, G. C. (2025). Rural schools and tech use for sustainability: the challenge of disconnection. *Education and Information Technologies*, *30*(9), 12557. https://doi.org/10.1007/s10639-024-13311-9

Aja, O. O., Asiabaka, C. C., Ani, A. O., & Matthews-Njoku, E. C. (2024). Comparative Study of the Socioeconomic Characteristics and Digital Literacy Level of Agricultural Extension Personnel in Imo and Ebonyi States, South-East, Nigeria. *Agricultural Sciences*, *15*(2), 230. https://doi.org/10.4236/as.2024.152013

Aker, J. C., Ghosh, I., & Burrell, J. (2016). The promise (and pitfalls) of ICT for agriculture initiatives. *Agricultural Economics*, *47*, 35. https://doi.org/10.1111/agec.12301

Akinlabi, A. A., & Dahunsi, F. M. (2021). Mobile broadband quality of service analysis using host-based performance measurements. *African Journal of Science Technology Innovation and Development*, *14*(4), 1083. https://doi.org/10.1080/20421338.2021.1936887

Alant, B. P., & Bakare, O. O. (2021). A case study of the relationship between smallholder farmers' ICT literacy levels and demographic data w.r.t. their use and adoption of ICT for weather forecasting. *Heliyon*, *7*(3). https://doi.org/10.1016/j.heliyon.2021.e06403

Alfonsi, R. M., Naidoo, M., &Gasparatos, A. (2024). Adoption and desirable characteristics of Information and Communication Technologies for urban small-scale food producers in South Africa. *Frontiers in Sustainable Food Systems*, *8*. https://doi.org/10.3389/fsufs.2024.1332978

Ali, A. S., Manias, D. M., Shami, A., &Muhaidat, S. (2023). Leveraging Large Language Models for DRL-Based Anti-Jamming Strategies in Zero Touch Networks. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2308.09376

Allen, L. K., &Kendeou, P. (2023). ED-AI Lit: An Interdisciplinary Framework for AI Literacy in Education. *Policy Insights from the Behavioral and Brain Sciences*, *11*(1), 3. https://doi.org/10.1177/23727322231220339

Al-Zahrani, A. M. (2024). Unveiling the shadows: Beyond the hype of AI in education. *Heliyon*, *10*(9). https://doi.org/10.1016/j.heliyon.2024.e30696

Arangurí, M., Mera, H., Noblecilla, W., & Lucini, C. (2025). Digital Literacy and Technology Adoption in Agriculture: A Systematic Review of Factors and Strategies [Review of *Digital Literacy and Technology Adoption in Agriculture: A Systematic Review of Factors and Strategies*]. *AgriEngineering*, *7*(9), 296. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/agriengineering7090296

Aricindy, A., Atmaja, H. T., & Wijaya, A. (2025). Higher education ICT integration in Africa: readiness, implementation and trajectory. *Perspectives Policy and Practice in Higher Education*, 1. https://doi.org/10.1080/13603108.2025.2453850

Aruleba, K., & Jere, N. (2022). Exploring digital transforming challenges in rural areas of South Africa through a systematic review of empirical studies [Review of *Exploring digital transforming challenges in rural areas of South Africa through a systematic review of empirical studies*]. *Scientific African*, *16*. Elsevier BV. https://doi.org/10.1016/j.sciaf.2022.e01190

Asante, B. O., Prah, S., Akutinga, S., Akusaki, E. T., &Ofosuhene, A. D. (2025). Climate resilience in the palm of a hand: digital financial inclusion and cocoa farmers' adoption of climate smart agricultural technologies in Ghana. *Future Business Journal*, *11*(1). https://doi.org/10.1186/s43093-025-00624-5

Azari, M. M., Solanki, S., Chatzinotas, S., Kodheli, O., Sallouha, H., Colpaert, A., Montoya, J. F. M., Pollin, S., Haqiqatnejad, A., Mostaani, A., Lagunas, E., &Ottersten, B. (2022). Evolution of Non-Terrestrial Networks From 5G to 6G: A Survey. *IEEE Communications Surveys & Tutorials*, *24*(4), 2633. https://doi.org/10.1109/comst.2022.3199901

Azeez, O. K., Yu, P., & Sesay, B. (2025). The Role of Digital Trade and Technological Advancements in Shaping Financial Resilience in Sub-Saharan Africa. *Sustainability*, *17*(8), 3399. https://doi.org/10.3390/su17083399

Baena, E., Testolina, P., Polese, M., Koutsonikolas, D., Jornet, J., & Melodia, T. (2025). *Space-O-RAN: Enabling Intelligent, Open, and Interoperable Non Terrestrial Networks in 6G*. https://doi.org/10.48550/ARXIV.2502.15936

Bakhadirov, M., Alasgarova, R., & Rzayev, J. (2024). Factors Influencing Teachers' Use of Artificial Intelligence for Instructional Purposes. *IAFOR Journal of Education*, *12*(2), 9. https://doi.org/10.22492/ije.12.2.01

Bali, B., Garba, E. J., Ahmadu, A. S., Takwate, K. T., &Malgwi, Y. M. (2024). Analysis of emerging trends in artificial intelligence for education in Nigeria. *Discover Artificial Intelligence*, *4*(1). https://doi.org/10.1007/s44163-024-00163-y

Bariah, L., Zhao, Q., Zou, H., Tian, Y., Bader, F., & Debbah, M. (2024). Large Generative AI Models for Telecom: The Next Big Thing? *IEEE Communications Magazine*, *62*(11), 84. https://doi.org/10.1109/mcom.001.2300364

Baumüller, H., & Kah, M. M. O. (2019). Going digital. In *Routledge eBooks* (p. 179). Informa. https://doi.org/10.4324/9780429401701-24

Boateng, G. (2024). Leveraging AI to Advance Science and Computing Education Across Africa: Challenges, Progress and Opportunities. In *Intelligent systems reference library* (p. 205). Springer Nature. https://doi.org/10.1007/978-3-031-71232-6_10

Boikanyo, D. H. (2025). Harnessing digital technologies for value chain optimization and societal transformation. *Business excellence and management*, *15*, 14. https://doi.org/10.24818/beman/2025.s.i.5-02

Bontsa, N. V., Mushunje, A., &Ngarava, S. (2023). Factors Influencing the Perceptions of Smallholder Farmers towards Adoption of Digital Technologies in Eastern Cape Province, South Africa. *Agriculture*, *13*(8), 1471. https://doi.org/10.3390/agriculture13081471

Bontsa, N. V., Mushunje, A., Ngarava, S., & Zhou, L. (2023). Utilisation of Digital Technologies by Smallholder Farmers in South Africa. *Suid-AfrikaanseTydskrif Vir Landbouvoorligting/South African Journal of Agricultural Extension*, *51*(4), 104. https://doi.org/10.17159/2413-3221/2023/v51n4a15337

Bontsa, N. V., Mushunje, A., Ngarava, S., & Zhou, L. (2024). Awareness and Perception of Digital Technologies by Smallholder Farmers in the Eastern Cape Province, South Africa. *Suid-AfrikaanseTydskrif Vir Landbouvoorligting/South African Journal of Agricultural Extension*, *52*(5), 73. https://doi.org/10.17159/2413-3221/2024/v52n5a16200

Briones, R., Galang, I. M., &Latigar, J. (2023). *Transforming Philippine Agri-Food Systems with Digital Technology: Extent, Prospects, and Inclusiveness*. https://doi.org/10.62986/dp2023.29

Cabrera-Castellanos, D. F., Aragón-Zavala, A., &Castañón, G. (2021). Closing Connectivity Gap: An Overview of Mobile Coverage Solutions for Not-Spots in Rural Zones [Review of *Closing Connectivity Gap: An Overview of Mobile Coverage Solutions for Not-Spots in Rural Zones*]. *Sensors*, *21*(23), 8037. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s21238037

Çelik, A., &Eltawil, A. M. (2024). *At the Dawn of Generative AI Era: A Tutorial-cum-Survey on New Frontiers in 6G Wireless Intelligence*. https://doi.org/10.36227/techrxiv.170775280.04186102/v2

Chaoub, A., Giordani, M., Lall, B., Bhatia, V., Kliks, A., Mendes, L. L., Rabie, K. M., Saarnisaari, H., Singhal, A., Zhang, N., Dixit, S., & Zorzi, M. (2021). 6G for Bridging the Digital Divide: Wireless Connectivity to Remote Areas. *IEEE Wireless Communications*, *29*(1), 160. https://doi.org/10.1109/mwc.001.2100137

Chen, N., Yang, J., Cheng, Z., Fan, X., Liu, Z., Huang, B., Zhao, Y., Huang, L., Du, X., &Guizani, M. (2024). GainNet: Coordinates the Odd Couple of Generative AI and 6G Networks. *IEEE Network*, *38*(5), 56. https://doi.org/10.1109/mnet.2024.3418671

Chen, Q., Guo, Z., Meng, W., Han, S., Li, C., & Quek, T. Q. S. (2024). A Survey on Resource Management in Joint Communication and Computing-Embedded SAGIN. *IEEE Communications Surveys & Tutorials*, 1. https://doi.org/10.1109/comst.2024.3421523

Chetty, S. B., Grace, D., Saunders, S., Harris, P., Tsiropoulou, E. E., Quek, T., & Ahmadi, H. (2025a). *Sovereign AI for 6G: Towards the Future of AI-Native Networks*. https://doi.org/10.48550/ARXIV.2509.06700

Chetty, S. B., Grace, D., Saunders, S. R., Harris, P. G., Tsiropoulou, E. E., Quek, T. Q. S., & Ahmadi, H. (2025b). Sovereign AI for 6G: Towards the Future of AI-Native Networks. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2509.06700

Chinelo, U. V., & Ayodeji, E. P. (2022). Leveraging on digital technology for financial inclusion of women agripreneurs in Southern Nigeria. *F1000Research*, *11*, 704. https://doi.org/10.12688/f1000research.122123.1

Choruma, D. J., Dirwai, T. L., Mutenje, M., Mustafa, M. A., Chimonyo, V. G. P., Jacobs-Mata, I., &Mabhaudhi, T. (2024). Digitalisation in agriculture: A scoping review of technologies in practice, challenges, and opportunities for smallholder farmers in sub-saharanafrica [Review of *Digitalisation in agriculture: A scoping review of technologies in practice, challenges, and opportunities for smallholder farmers in sub-saharanafrica*]. *Journal of Agriculture and Food Research*, *18*, 101286. Elsevier BV. https://doi.org/10.1016/j.jafr.2024.101286

Coggins, S., McCampbell, M., Sharma, A., Sharma, R., Haefele, S. M., Karki, E., Hetherington, J., Smith, J., & Brown, B. (2021). How have smallholder farmers used digital extension tools? Developer and user voices from Sub-Saharan Africa, South Asia and Southeast Asia. *Global Food Security*, *32*, 100577. https://doi.org/10.1016/j.gfs.2021.100577

Daher, R. F. (2025). Integrating AI literacy into teacher education: a critical perspective paper. *Discover Artificial Intelligence*, *5*(1). https://doi.org/10.1007/s44163-025-00475-7

Djatmiko, G. H., Sinaga, O., &Pawirosumarto, S. (2025). Digital Transformation and Social Inclusion in Public Services: A Qualitative Analysis of E-Government Adoption for Marginalized Communities in Sustainable Governance. *Sustainability*, *17*(7), 2908. https://doi.org/10.3390/su17072908

Dlamini, R., & Ndzinisa, N. (2025). Towards a critical discourse on artificial intelligence and its misalignment in sub-Saharan Africa: Through an equality, equity, and decoloniality lens. *Journal of Education*, *98*, 42. https://doi.org/10.17159/2520-9868/i98a03

Doerksen, K., Fibaek, C., Schneider, R., Kim, D.-H., &Tingzon, I. (2024). *Predicting Internet Connectivity in Schools: A Feasibility Study Leveraging Multi-modal Data and Location Encoders in Low-Resource Settings*. https://doi.org/10.48550/ARXIV.2412.12188

Don, I. K. I. (2025). Digital economy and agricultural development: An analysis on BIMSTEC countries. *Journal of Infrastructure Policy and Development*, *9*(1), 10786. https://doi.org/10.24294/jipd10786

Dosumu, J. (2024). Overcoming Infrastructural Barriers to Digital Literacy in Rural Nigeria. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4992050

Duca, F., Mutua, A., Tetley-Brown, L., Karuri-Sebina, G., & Backhouse, J. (2024). Smart cities governance in the Southern African Development Community (SADC) region: A systematic review of the literature [Review of *Smart cities governance in the Southern African Development Community (SADC) region: A systematic review of the literature*]. *Research Square (Research Square)*. Research Square (United States). https://doi.org/10.21203/rs.3.rs-4382210/v1

Effah, E., Ghartey, G., Aidoo, J. K., &Thiaré, O. (2024). Hardware Development and Evaluation of Multihop Cluster-Based Agricultural IoT Based on Bluetooth Low-Energy and LoRa Communication Technologies. *Sensors*, *24*(18), 6113. https://doi.org/10.3390/s24186113

Ehimuan, B., Anyanwu, A., Olorunsogo, T., Akindote, O. J., Abrahams, T. O., & Reis, O. (2024). Digital inclusion initiatives: Bridging the connectivity gap in Africa and the USA – A review [Review of *Digital inclusion initiatives: Bridging the connectivity gap in Africa and the USA – A review*]. *International Journal of Science and Research Archive*, *11*(1), 488. https://doi.org/10.30574/ijsra.2024.11.1.0061

Elifas, T. N., &Simuja, C. (2024). The pedagogical insights of mathematics teachers integrating artificial intelligence in rural upper-primary schools in Namibia. *Interdisciplinary Journal of Education Research*, *6*, 1. https://doi.org/10.38140/ijer-2024.vol6.37

Engås, K. G., Raja, J. Z., &Neufang, I. F. (2023). Decoding technological frames: An exploratory study of access to and meaningful engagement with digital technologies in agriculture. *Technological Forecasting and Social Change*, *190*, 122405. https://doi.org/10.1016/j.techfore.2023.122405

Evurulobi, C. I., Dagunduro, A. O., &Ajuwon, O. A. (2024). Theoretical perspectives on digital literacy programs: A comparative study of initiatives in Africa and the United States. *World Journal of Advanced Research and Reviews*, *23*(3), 2708. https://doi.org/10.30574/wjarr.2024.23.3.2853

Falebita, O. S., & Kok, P. J. (2024). Strategic goals for artificial intelligence integration among STEM academics and undergraduates in African higher education: a systematic review [Review of *Strategic goals for artificial intelligence integration among STEM academics and undergraduates in African higher education: a systematic review*]. *Discover Education*, *3*(1). Springer Science+Business Media. https://doi.org/10.1007/s44217-024-00252-1

Fang, X., Feng, W., Wei, T., Chen, Y., Ge, N., & Wang, C. (2021). 5G Embraces Satellites for 6G Ubiquitous IoT: Basic Models for Integrated Satellite Terrestrial Networks. *IEEE Internet of Things Journal*, *8*(18), 14399. https://doi.org/10.1109/jiot.2021.3068596

Farinha, C. S. e S., & Martins, F. (2025). 5G Internet in Rural Areas: Impacts, Challenges and Sustainable Strategies for Development. *Revista de Gestão Social e Ambiental*, *19*(1). https://doi.org/10.24857/rgsa.v19n1-177

Fausiyat, A. T. (2025). Assessing digital market access and mobile finance tools in boosting agribusiness growth among rural farming communities. *World Journal of Advanced Research and Reviews*, *27*(1), 659. https://doi.org/10.30574/wjarr.2025.27.1.2579

Flowers, B., & Tanner, M. (2024). Exploring the Digital Readiness of Underprivileged Secondary Schools in South Africa. In *IFIP advances in information and communication technology* (p. 328). Springer Science+Business Media. https://doi.org/10.1007/978-3-031-66982-8_23

Funa, A., & Gabay, R. A. E. (2024). Policy guidelines and recommendations on AI use in teaching and learning: A meta-synthesis study. *Social Sciences & Humanities Open*, *11*, 101221. https://doi.org/10.1016/j.ssaho.2024.101221

Geng, W., Liu, L., Zhao, J., Kang, X., & Wang, W. (2024). Digital Technologies Adoption and Economic Benefits in Agriculture: A Mixed-Methods Approach. *Sustainability*, *16*(11), 4431. https://doi.org/10.3390/su16114431

Giest, S. (2025). The intersection of digital and social infrastructures in (a)spatial policymaking. *Policy Sciences*. https://doi.org/10.1007/s11077-025-09569-6

Gikunda, K. (2024). Empowering Africa: An In-depth Exploration of the Adoption of Artificial Intelligence Across the Continent. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2401.09457

Glavanits, J., & Szabó, T. (2024). *FinTech Solutions Supporting Sustainable Agriculture ? Lessons from Africa*. 97. https://doi.org/10.1145/3670243.3672435

Goggin, G. (2025). *Mobile AI: Communication and Mobility After the Smartphone*. *1*(1). https://doi.org/10.1007/s44382-025-00002-3

Gumbi, N., Gumbi, L., &Twinomurinzi, H. (2023). Towards Sustainable Digital Agriculture for Smallholder Farmers: A Systematic Literature Review. *Sustainability*, *15*(16), 12530. https://doi.org/10.3390/su151612530

Hackfort, S. (2021). Patterns of Inequalities in Digital Agriculture: A Systematic Literature Review. *Sustainability*, *13*(22), 12345. https://doi.org/10.3390/su132212345

Haetami, H. (2025). AI-Driven Educational Transformation in Indonesia: From Learning Personalization to Institutional Management. *AL-ISHLAH Jurnal Pendidikan*, *17*(2), 1819. https://doi.org/10.35445/alishlah.v17i2.7448

Heeks, R., & Bukht, R. (2018). Digital Economy Policy in Developing Countries. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3540027

Homssi, B. A., & Al-Hourani, A. (2021). Modeling Uplink Coverage Performance in Hybrid Satellite-Terrestrial Networks. *IEEE Communications Letters*, *25*(10), 3239. https://doi.org/10.1109/lcomm.2021.3103942

Hornuf, L., Safari, K., &Voshaar, J. (2024). Mobile Fintech Adoption in Sub-Saharan Africa: A Systematic Literature Review and Meta-Analysis. *Research in International Business and Finance*, *73*, 102529. https://doi.org/10.1016/j.ribaf.2024.102529

Hove, M. T., Ngwenya, H., &Madhazi, K. (2024). Digital Advisory Systems in Zimbabwean Agriculture: Opportunities and Constraints. *Agricultural Sciences*, *15*(11), 1315. https://doi.org/10.4236/as.2024.1511072

Höyhtyä, M., Anttonen, A., Majanen, M., Yastrebova, A., Varga, M., Lodigiani, L., Corici, M., &Zope, H. (2024). Multi-Layered Satellite Communications Systems for Ultra-High Availability and Resilience. *Electronics*, *13*(7), 1269. https://doi.org/10.3390/electronics13071269

Isotani, S., Bittencourt, I. I., Challco, G. C., Dermeval, D., & Mello, R. F. (2023). AIED Unplugged: Leapfrogging the Digital Divide to Reach the Underserved. In *Communications in computer and information science* (p. 772). Springer Science+Business Media. https://doi.org/10.1007/978-3-031-36336-8_118

Jamshed, M. A., Kaushik, A., Dajer, M., Guidotti, A., Parzysz, F., Lagunas, E., Renzo, M. D., Chatzinotas, S., & Dobre, O. A. (2025). Non-Terrestrial Networks for 6G: Integrated, Intelligent and Ubiquitous Connectivity. *IEEE Communications Standards Magazine*, 1. https://doi.org/10.1109/mcomstd.2025.3572635

Janbi, N. F., Katib, I., Albeshri, A., & Mehmood, R. (2020). Distributed Artificial Intelligence-as-a-Service (DAIaaS) for Smarter IoE and 6G Environments. *Sensors*, *20*(20), 5796. https://doi.org/10.3390/s20205796

Javaid, S., Khalil, R. A., Saeed, N., He, B., &Alouini, M. (2024). Leveraging Large Language Models for Integrated Satellite-Aerial-Terrestrial Networks: Recent Advances and Future Directions. *IEEE Open Journal of the Communications Society*, 1. https://doi.org/10.1109/ojcoms.2024.3522103

Kamutuezu, E. U., Winschiers-Theophilus, H., & Peters, A. (2021). An Exploration of Factors Influencing the Adoption of ICT Enabled Entrepreneurship Applications in Namibian Rural Communities. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2108.09789

Kansiime, M. K., Mugambi, I., Rware, H., Alokit, C., Aliamo, C., Zhang, F., LATZKO, J., YANG, P., KARANJA, D., & Romney, D. L. (2021). CHALLENGES AND CAPACITY GAPS IN SMALLHOLDER ACCESS TO DIGITAL EXTENSION AND ADVISORY SERVICES IN KENYA AND UGANDA. *Frontiers of Agricultural Science and Engineering*, *9*(4), 642. https://doi.org/10.15302/j-fase-2021423

Karapantelakis, A., Nikou, A., Kattepur, A., Martins, J., Mokrushin, L., Mohalik, S. K., Orlic, M., &Feljan, A. V. (2024). *A Survey on the Integration of Generative AI for Critical Thinking in Mobile Networks*. https://doi.org/10.48550/ARXIV.2404.06946

Kelly, A. M., &Rutazihana, P. N. (2024). Digital Divide and its Implications for Education in the Post-covid-19 Era in Sub-Saharan Africa. *Innovation and Education*, *6*(2), 108. https://doi.org/10.1163/25248502-bja00007

Khan, M. S., Umer, H., &Faruqe, F. (2024). Artificial intelligence for low income countries. *Humanities and Social Sciences Communications*, *11*(1). https://doi.org/10.1057/s41599-024-03947-w

Khan, N., Xu, X., Khayyam, M., & Raziq, A. (2024). Toward making the field talk: assessing the relationship between digital technology and sustainable food production in agricultural regions. *Frontiers in Nutrition*, *11*, 1462438. https://doi.org/10.3389/fnut.2024.1462438

Kibinda, N. M., Shao, D., Mwogosi, A., &Mambile, C. (2025). Broadband infrastructure sharing as a catalyst for rural digital economy: A systematic review for developing countries [Review of *Broadband infrastructure sharing as a catalyst for rural digital economy: A systematic review for developing countries*]. *Telecommunications Policy*, *49*(8), 103028. Elsevier BV. https://doi.org/10.1016/j.telpol.2025.103028

Kitole, F. A., Mkuna, E., &Sesabo, J. K. (2023). Digitalization and agricultural transformation in developing countries: Empirical evidence from Tanzania agriculture sector. *Smart Agricultural Technology*, *7*, 100379. https://doi.org/10.1016/j.atech.2023.100379

Kondoro, A. M. (2025). *AI Writing Assistants in Tanzanian Universities: Adoption Trends, Challenges, and Opportunities*. 37. https://doi.org/10.18653/v1/2025.in2writing-1.4

Kumar, A., Anbumozhi, V., Babu, S. C., Bollino, C. A., Diyanah, S. M., Hanifah, V. W., Hidayat, S., Kozono, M., Nugroho, A. E., Permani, R., Sahara, S., Syukur, M., &Wardhana, I. W. (2022). Digital transformation of agri-food system: policy pathways for greater socio-economic inclusion, sustainability, and international cooperation. *Zenodo (CERN European Organization for Nuclear Research)*. https://doi.org/10.5281/zenodo.7415603

Kuteesa, K. N., Akpuokwe, C. U., & Udeh, C. A. (2024). THEORETICAL PERSPECTIVES ON DIGITAL DIVIDE AND ICT ACCESS: COMPARATIVE STUDY OF RURAL COMMUNITIES IN AFRICA AND THE UNITED STATES. *Computer Science & IT Research Journal*, *5*(4), 839. https://doi.org/10.51594/csitrj.v5i4.1045

Ky, S. S. (2025). Empowering Sub-Saharan farmers: The transformative effect of mobile money in agriculture. *Journal of Rural Studies*, *117*, 103637. https://doi.org/10.1016/j.jrurstud.2025.103637

Lai, B., Wen, J., Kang, J., Du, H., Nie, J., Yi, C., Kim, D. I., & Xie, S. (2023). Resource-efficient Generative Mobile Edge Networks in 6G Era: Fundamentals, Framework and Case Study. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2312.12063

Li, Z., Wang, J., Zhao, S., Wang, Q., & Wang, Y. (2025). Evolving Towards Artificial-Intelligence-Driven Sixth-Generation Mobile Networks: An End-to-End Framework, Key Technologies, and Opportunities. *Applied Sciences*, *15*(6), 2920. https://doi.org/10.3390/app15062920

Liu, B., & Zhou, J. (2023). Digital Literacy, Farmers' Income Increase and Rural Internal Income Gap. *Sustainability*, *15*(14), 11422. https://doi.org/10.3390/su151411422

López, M., Damsgaard, S. B., Rodríguez, I., & Mogensen, P. (2023). Connecting Rural Areas: an Empirical Assessment of 5G Terrestrial-LEO Satellite Multi-Connectivity. *2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring)*, 1. https://doi.org/10.1109/vtc2023-spring57618.2023.10199206

Lyu, Z., Jing, Z., & Yang, X. (2025). Bridging the digital divide for sustainable agriculture: how digital adoption strengthens farmer livelihood resilience. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1628588

Magesa, M. M., Jonathan, J., &Urassa, J. K. (2023). Digital Literacy of Smallholder Farmers in Tanzania. *Sustainability*, *15*(17), 13149. https://doi.org/10.3390/su151713149

Mahboob, S., & Liu, L. (2024). Revolutionizing Future Connectivity: A Contemporary Survey on AI-Empowered Satellite-Based Non-Terrestrial Networks in 6G. *IEEE Communications Surveys & Tutorials*, *26*(2), 1279. https://doi.org/10.1109/comst.2023.3347145

Makapela, M., Alexander, G., &Tshelane, M. (2025). Enhancing Agricultural Productivity Among Emerging Farmers Through Data-Driven Practices. *Sustainability*, *17*(10), 4666. https://doi.org/10.3390/su17104666

Makaula, Z. (2021). Information and communication technologies (ICT) towards agricultural development in rural areas: case of smallholder farmers in Umzimvubu local municipality of the Eastern Cape Province in South Africa. *Suid-AfrikaanseTydskrif Vir Landbouvoorligting/South African Journal of Agricultural Extension*, *49*(1), 81. https://doi.org/10.17159/2413-3221/2021/v49n1a10779

Makeleni, S., Mutongoza, B. H., &Linake, M. A. (2023). Language Education and Artificial Intelligence: An Exploration of Challenges Confronting Academics in Global South Universities. *Journal of Culture and Values in Education*, *6*(2), 158. https://doi.org/10.46303/jcve.2023.14

Maltitz, L. von, Niekerk, J. V., & Davis, K. A. (2024). The Digital Readiness of Agricultural Advisory Professionals: A South African Case Study. *Suid-AfrikaanseTydskrif Vir Landbouvoorligting/South African Journal of Agricultural Extension*, *52*(4), 47. https://doi.org/10.17159/2413-3221/2024/v52n4a16851

Manning, L. (2024). Innovating in an Uncertain World: Understanding the Social, Technical and Systemic Barriers to Farmers Adopting New Technologies. *Challenges*, *15*(2), 32. https://doi.org/10.3390/challe15020032

Manzoor, F., Wei, L., Siraj, M., Lu, X., &Qiyang, G. (2025). Digital agriculture technology adoption in low and middle-income countries—a review of contemporary literature. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1621851

Mapanje, O., Karuaihe, S., Machethe, C., & Amis, M. (2023). Financing Sustainable Agriculture in Sub-Saharan Africa: A Review of the Role of Financial Technologies [Review of *Financing Sustainable Agriculture in Sub-Saharan Africa: A Review of the Role of Financial Technologies*]. *Sustainability*, *15*(5), 4587. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su15054587

Marshall, A., Dezuanni, M., Burgess, J., Thomas, J., & Wilson, C. (2020). Australian farmers left behind in the digital economy – Insights from the Australian Digital Inclusion Index. *Journal of Rural Studies*, *80*, 195. https://doi.org/10.1016/j.jrurstud.2020.09.001

Matchaya, G., Aheeyar, M. M. M., Ebrahim, G. Y., Langan, S., Rex, W., Ajayi, O. C., Afun-Ogidan, O., Wouterse, F., Fakudze, B., Kasoma-Pele, W., Rebelo, L., Jacobs-Mata, I., & Amarnath, G. (2024). *The potential for digital adaptation in agriculture in the Zambezi River Basin countries: regional assessment report*. https://doi.org/10.5337/2024.228

Mazwane, S., Makhura, M. N., & Ginige, A. (2024). The Extent and Patterns of Digitalization in Proactive Land Acquisition Strategy (PLAS) Farms in South Africa. *Turkish Journal of Agriculture - Food Science and Technology*, *12*(10), 1635. https://doi.org/10.24925/turjaf.v12i10.1635-1648.6773

Mazwane, S., Makhura, M. N., &Senyolo, M. P. (2022). Important Policy Parameters for the Development of Inclusive Digital Agriculture: Implications for the Redistributive Land Reform Program in South Africa. *Agriculture*, *12*(12), 2129. https://doi.org/10.3390/agriculture12122129

Mehrabi, Z., McDowell, M. J., Ricciardi, V., Levers, C., Martínez, J. D., Mehrabi, N., Wittman, H., Ramankutty, N., & Jarvis, A. (2020). The global divide in data-driven farming. *Nature Sustainability*, *4*(2), 154. https://doi.org/10.1038/s41893-020-00631-0

Mhlanga, D., & Ndhlovu, E. (2023). Digital Technology Adoption in the Agriculture Sector: Challenges and Complexities in Africa. *Human Behavior and Emerging Technologies*, *2023*, 1. https://doi.org/10.1155/2023/6951879

Mkhonto, B. S., & Mubangizi, B. C. (2024). Digital Divide or Digital Bridge? Evaluating the Impact of ICT Integration in South Africa's Rural Schools. *International Journal of Social Science Research and Review*, *7*(7), 132. https://doi.org/10.47814/ijssrr.v7i7.2142

Mnkandla, A., & Volk, J. (2025). Closing the Digital Gap: Challenges and Prospects for Gender Equality in South Africa. *International Journal of Technology and Systems*, *10*(2), 27. https://doi.org/10.47604/ijts.3224

Modiba, F. S., & Kaye, S.-A. (2023). EVALUATION OF INFORMATION AND COMMUNICATION TECHNOLOGIES (ICTs) TOOLS CONTRIBUTING TO RURAL DEVELOPMENT. *Russian Journal of Agricultural and Socio-Economic Sciences*, *142*(10), 19. https://doi.org/10.18551/rjoas.2023-10.03

Mohsin, M. A., Ahmad, J., Nawaz, M. H., & Jamshed, M. A. (2025). *Towards 6G Intelligence: The Role of Generative AI in Future Wireless Networks*. https://doi.org/10.48550/ARXIV.2508.19495

Mothobi, O., &Kebotsamang, K. (2024). The impact of network coverage on adoption of Fintech and financial inclusion in sub-Saharan Africa. *Journal of Economic Structures*, *13*(1). https://doi.org/10.1186/s40008-023-00326-7

Mugari, E., Mathebula, N., Mogale, T. E., Mamabolo, E., Mashala, M. J., Mabitsela, K., &Ayisi, K. K. (2025). Influence of public agricultural extension services on sustainable land management practice adoption among smallholder farmers in FetakgomoTubatse Local Municipality, South Africa. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1618938

Munthali, N. (2021). *Innovation intermediation in a digital age : Broadening extension service delivery in Ghana*. https://doi.org/10.18174/534964

Muringa, T. P. (2025). Exploring ethical dilemmas and institutional challenges in AI adoption: a study of South African universities. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1628019

Muromba, P., Keeni, M., & Fuyuki, K. (2025). A Systematic Review of Mobile Agricultural Service Applications for Smallholder Farmers in Sub-Saharan Africa: Perspectives from the Technology Acceptance Model [Review of *A Systematic Review of Mobile Agricultural Service Applications for Smallholder Farmers in Sub-Saharan Africa: Perspectives from the Technology Acceptance Model*]. *Research Square (Research Square)*. Research Square (United States). https://doi.org/10.21203/rs.3.rs-5911289/v1

Mushi, G. E., Serugendo, G. D. M., & Burgi, P. (2022). Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review [Review of *Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review*]. *Sustainability*, *14*(4), 2415. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su14042415

Mustafa, A. N. (2025). Reimagining education in the age of Artificial Intelligence: Challenges and strategies for developing nations. *International Journal of Science and Research Archive*, *16*(2), 291. https://doi.org/10.30574/ijsra.2025.16.2.2029

Mwansa, G., Ngandu, M. R., &Mkwambi, Z. (2025). Bridging the digital divide: exploring the challenges and solutions for digital exclusion in rural South Africa. *Discover Global Society*, *3*(1). https://doi.org/10.1007/s44282-025-00189-2

Navaie, K. (2024). Personal Data Protection in AI-Native 6G Systems. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4874341

Nezami, Z., Hafeez, M., Djemame, K., & Zaidi, S. A. R. (2024). Generative AI on the Edge: Architecture and Performance Evaluation. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2411.17712

Ngulube, P. (2025). Leveraging information and communication technologies for sustainable agriculture and environmental protection among smallholder farmers in tropical Africa. *Discover Environment*, *3*(1). https://doi.org/10.1007/s44274-025-00190-1

Nguyen, C. T., Saputra, Y. M., Huynh, N. V., Nguyen, T. N., Hoang, D. T., Nguyen, D. N., Pham, V., Vozňák, M., Chatzinotas, S., & Tran, D.-H. (2024). Emerging Technologies for 6G Non-Terrestrial-Networks: From Academia to Industrial Applications. *IEEE Open Journal of the Communications Society*, *5*, 3852. https://doi.org/10.1109/ojcoms.2024.3418574

Nkandu, P., & Phiri, J. (2022). Assessing the Effect of ICTs on Agriculture Productivity Based on the UTAUT Model in Developing Countries. Case Study of Southern Province in Zambia. *Open Journal of Business and Management*, *10*(6), 3436. https://doi.org/10.4236/ojbm.2022.106169

Ntorukiri, T. B., Kirugua, J. M., & Kirimi, F. (2022). Policy and infrastructure challenges influencing ICT implementation in universities: a literature review [Review of *Policy and infrastructure challenges influencing ICT implementation in universities: a literature review*]. *Discover Education*, *1*(1). Springer Science+Business Media. https://doi.org/10.1007/s44217-022-00019-6

Nwafor, C. U. (2020). *An Integrated Conceptual Framework for ICT-based Market Information Source Adoption among Smallholder Farmers*. https://doi.org/10.20944/preprints202003.0163.v1

Nwangwu, K. N., Onyenekwe, C. S., Opata, P. I., Ume, C. O., & Ume, N. N. C. (2024). Can digital technology promote market participation among smallholder farmers? *The International Food and Agribusiness Management Review*, *27*(4), 706. https://doi.org/10.22434/ifamr2023.0065

Ofosu-Ampong, K., Abera, W., Mesfin, T., & Abate, T. (2025). Digital agro-advisory tools in the global south: a behavioural analysis of impacts, and future directions. *Discover Agriculture*, *3*(1). https://doi.org/10.1007/s44279-025-00190-y

Oklikah, D. O., Abdulai, A., & Abban, I. (2023). Farmer Socio-Demography and Beyond? Smallholder Perceived Challenges and the Intention to Adopt Digital Tools and Services in Northern Ghana. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4526886

Okonkwo, S. N. (2025). *Digital Inclusion in Africa: Bridging the Divide*. https://doi.org/10.2139/ssrn.5151540

Oladunjoye, O. N., & Chaka, M. (2025). Tourism Inflow and Economic Growth in South Africa: The Role of Digital Inclusion. *International Journal of Economics and Financial Issues*, *15*(6), 653. https://doi.org/10.32479/ijefi.20431

Olayinka, T. A., Waghid, Y., Mataka, T. W., & Adegoke, O. (2024). Demystifying Lesotho, Rwandan and Nigerian educators' viewpoints on smart technologies supporting AI in higher education. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12820-x

Olorunfemi, O. D., Mamiane, T. A., & Matiwane, M. B. (2024). Investigating access and use of digital tools for agriculture among rural farmers: A case study of Nkomazi Municipality, South Africa. *Open Agriculture*, *9*(1). https://doi.org/10.1515/opag-2022-0380

O'Neill, J., Marivate, V., Glover, B., Karanu, W., Tadesse, G. A., Gyekye, A., Makena, A., Rosslyn-Smith, W., Grollnek, M., Wayua, C., Baguma, R., Maduke, A., Spencer, S., Kandie, D., Maari, D. N., Mutangana, N., Axmed, M., Kamau, N., Adamu, M., … Nyairo, S. (2024). AI and the Future of Work in Africa White Paper. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2411.10091

Osondu, J., Francois, E. J., & Strycker, J. (2024). Artificial intelligence as a policy response to teaching and learning issues in education in Ghana. *Journal of Global Education and Research*, *8*(3), 236. https://doi.org/10.5038/2577-509x.8.3.1361

Paget, N., McCampbell, M., Ba, B., Bamba, M., Cesaro, J., Ferrari, S., Notaro, M., Okry, F., Richebourg, C., & Bonnet, P. (2025). Achieving inclusive digital development: A frugal strategy based on lessons from three West African smallholder agriculture value chains. *Technological Forecasting and Social Change*, *220*, 124287. https://doi.org/10.1016/j.techfore.2025.124287

Panwar, A., & Sahoo, S. K. (2025). Transforming Rural Agriculture Through Technology: An Empirical Study on the Socio-Economic and Sustainable Impacts of Digital Platforms. *International Journal For Multidisciplinary Research*, *7*(3). https://doi.org/10.36948/ijfmr.2025.v07i03.47805

Patel, S., &Ragolane, M. (2024). The Implementation of Artificial Intelligence in South African Higher Education Institutions: Opportunities and Challenges. *Technium Education and Humanities*, *9*, 51. https://doi.org/10.47577/teh.v9i.11452

Plastras, S., Polymeni, S., Skoutas, D. N., Kormentzas, G., &Skianis, C. (2023). Sustainable Networking Solutions in Remote IoT Environments: Use Cases, Challenges, and Solutions for Smart Agriculture. In *Key challenges in geography* (p. 307). Springer International Publishing. https://doi.org/10.1007/978-3-031-40747-5_17

Ramírez-Arroyo, A., López, M., Rodríguez, I., Damsgaard, S. B., & Mogensen, P. (2024). *Multi-Connectivity Solutions for Rural Areas: Integrating Terrestrial 5G and Satellite Networks to Support Innovative IoT Use Cases*. https://doi.org/10.48550/ARXIV.2411.06979

Rayhan, Md. J., Rahman, S. M. M., Mamun, A. A., Saif, A. N. M., Islam, K. M. A., Alom, Md. M., & Hafiz, N. (2024). FinTech solutions for sustainable agricultural value chains: A perspective from smallholder farmers. *Business Strategy & Development*, *7*(2). https://doi.org/10.1002/bsd2.358

Ren, X., & Wu, M. L. (2025). Examining Teaching Competencies and Challenges While Integrating Artificial Intelligence in Higher Education. *TechTrends*. https://doi.org/10.1007/s11528-025-01055-3

Rey-Moreno, C. (2015). *Community Telco: An acceptable solution for providing affordable communications in rural areas of South Africa*. https://burjcdigital.urjc.es/handle/10115/13643

Robb, G., &Paelo, A. (2020). Competitive dynamics of telecommunications markets in South Africa, Tanzania, Zambia, and Zimbabwe. In *Working Paper Series*. https://doi.org/10.35188/unu-wider/2020/840-5

Sai, S., Prasad, M., Dashore, G., Chamola, V., & Sikdar, B. (2024). On-Device Generative AI: The Need, Architectures, and Challenges. *IEEE Consumer Electronics Magazine*, *14*(4), 21. https://doi.org/10.1109/mce.2024.3518761

Samuel-Okon, A. D., & Abejide, O. O. (2024). Bridging the Digital Divide: Exploring the Role of Artificial Intelligence and Automation in Enhancing Connectivity in Developing Nations. *Journal of Engineering Research and Reports*, *26*(6), 165. https://doi.org/10.9734/jerr/2024/v26i61170

Sands, J. (2025). Educational Policies Impacted by the Utilization of AI. *The Scholarship Without Borders Journal*, *3*(2). https://doi.org/10.57229/2834-2267.1063

Sasere, O. B., &Makhasane, S. D. (2023). Adult learning theory tenets: A panacea to ICT skills gaps among educators in South Africa. *Journal of Education*, *92*, 58. https://doi.org/10.17159/2520-9868/i92a04

Satpathy, B. (2022). Digital transformation for sustainable agriculture: a progressive method for smallholder farmers. *Current Science*, *123*(12), 1436. https://doi.org/10.18520/cs/v123/i12/1436-1440

Selemela, A., Khwela, M. N., &Selelo, M. E. (2023). The role of the fourth industrial revolution in achieving economic development: challenges and opportunities. *International Journal of Research in Business and Social Science (2147-4478)*, *12*(7), 244. https://doi.org/10.20525/ijrbs.v12i7.2808

Sen, L. T. H., Phương, L. T., Chou, P., Dacuyan, F. B., Nyberg, Y., &Wetterlind, J. (2025). The Opportunities and Barriers in Developing Interactive Digital Extension Services for Smallholder Farmers as a Pathway to Sustainable Agriculture: A Systematic Review [Review of *The Opportunities and Barriers in Developing Interactive Digital Extension Services for Smallholder Farmers as a Pathway to Sustainable Agriculture: A Systematic Review*]. *Sustainability*, *17*(7), 3007. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su17073007

Sevim, N., İbrahim, M., & Ekin, S. (2024). Large Language Models (LLMs) Assisted Wireless Network Deployment in Urban Settings. *2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall)*, 1. https://doi.org/10.1109/vtc2024-fall63153.2024.10757657

Shahid, M., Das, K., Islam, T. U., Somiah, C., Qiao, D., Ahmad, A., Song, J., Zhu, Z., Babu, S., Guan, Y., Chakraborty, T., Jog, S., Chandra, R., & Zhang, H. (2024). *Wireless Spectrum in Rural Farmlands: Status, Challenges and Opportunities*. https://doi.org/10.48550/ARXIV.2407.04561

Sharma, K., &Shivandu, S. K. (2024). Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture. *Sensors International*, *5*, 100292. https://doi.org/10.1016/j.sintl.2024.100292

Shokrnezhad, M., & Taleb, T. (2025). An Autonomous Network Orchestration Framework Integrating Large Language Models with Continual Reinforcement Learning. *IEEE Communications Magazine*, *63*(8), 78. https://doi.org/10.1109/mcom.001.2400526

Sibiya, P. T., Chuma, K. G., & Jacobs, L. (2025). Computer proficiency for social development in the rural areas of KwaZulu-Natal. *South African Journal of Information Management*, *27*(1). https://doi.org/10.4102/sajim.v27i1.1960

Smidt, H. J., & Jokonya, O. (2021). Factors affecting digital technology adoption by small-scale farmers in agriculture value chains (AVCs) in South Africa. *Information Technology for Development*, *28*(3), 558. https://doi.org/10.1080/02681102.2021.1975256

Stam, G. van. (2021). Access to Digital Platforms: Can “Mobile” Network Coverage Reports be Relied Upon? Observations from Rural Zambia and Zimbabwe. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2108.10086

Steinke, J., Schumann, C., Langan, S., Müller, A., Opola, F. O., Ortiz-Crespo, B., & Etten, J. van. (2024). Fostering social inclusion in development-oriented digital food system interventions. *Agricultural Systems*, *215*, 103882. https://doi.org/10.1016/j.agsy.2024.103882

Sufian, F. D., Nico, G., &Azzarri, C. (2023). *Examining the gender digital divide: A case study from rural Nigeria*. https://doi.org/10.2499/p15738coll2.136918

Tarkoma, S., Morabito, R., & Sauvola, J. (2023). AI-native Interconnect Framework for Integration of Large Language Model Technologies in 6G Systems. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2311.05842

Thaher, N., Shibli, R. A., Pesce, V., & Al-Ghosoun, A. (2025). Drivers and barriers in embracing digital farming: Insights from the smallholder farmers in the NENA region. *Emirates Journal of Food and Agriculture*, *37*, 1. https://doi.org/10.3897/ejfa.2025.151184

Tilley, A., Lam, R. D., Lazo, D. P. L., Lopes, J. D. R., Costa, D. F. D., Belo, M. D. F., Silva, J. D., Cruz, G. da S., &Rossignoli, C. (2024). The impacts of digital transformation on fisheries policy and sustainability: Lessons from Timor-Leste. *Environmental Science & Policy*, *153*, 103684. https://doi.org/10.1016/j.envsci.2024.103684

Umer, M., Mohsin, M. A., Nasir, A. A., Abou-Zeid, H., & Hassan, S. Al. (2025). *Intelligent Spectrum Sharing in Integrated TN-NTNs: A Hierarchical Deep Reinforcement Learning Approach*. https://doi.org/10.48550/ARXIV.2503.06720

Valdivieso, T., & González, O. A. G. (2025). Generative AI Tools in Salvadoran Higher Education: Balancing Equity, Ethics, and Knowledge Management in the Global South. *Education Sciences*, *15*(2), 214. https://doi.org/10.3390/educsci15020214

Vesna, L. (2025). Digital Divide in AI-Powered Education: Challenges and Solutions for Equitable Learning. *Journal of Information Systems Engineering & Management*, *10*, 300. https://doi.org/10.52783/jisem.v10i21s.3327

Vijayakumar, S., Murugaiyan, V., Ilakkiya, S., Kumar, V., Sundaram, R. M., & Kumar, R. M. (2025). Opportunities, challenges, and interventions for agriculture 4.0 adoption. *Discover Food*, *5*(1). https://doi.org/10.1007/s44187-025-00576-3

Vuruma, S. K. R., Margetts, A., Su, J., Ahmed, F., & Srivastava, B. (2024). *From Cloud to Edge: Rethinking Generative AI for Low-Resource Design Challenges*. https://doi.org/10.48550/ARXIV.2402.12702

Wang, S., Mwalupaso, G. E., & Akter, A. (2025). Nexus of women's participation in smallholder financial inclusion programs and economic efficiency: implications for poverty alleviation. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1613678

Wang, X., Tang, Z., Guo, J., Meng, T., Wang, C., Wang, T., & Jia, W. (2025). Empowering Edge Intelligence: A Comprehensive Survey on On-Device AI Models [Review of *Empowering Edge Intelligence: A Comprehensive Survey on On-Device AI Models*]. *ACM Computing Surveys*. Association for Computing Machinery. https://doi.org/10.1145/3724420

Wu, G., & Peng, Q. (2024). Bridging the Digital Divide: Unraveling the Determinants of FinTech Adoption in Rural Communities. *SAGE Open*, *14*(1). https://doi.org/10.1177/21582440241227770

Xiao, A., Xu, Z., Škare, M., Qin, Y., & Wang, X. (2024). Bridging the digital divide: the impact of technological innovation on income inequality and human interactions. *Humanities and Social Sciences Communications*, *11*(1). https://doi.org/10.1057/s41599-024-03307-8

Yang, H., Lambotharan, S., Derakhshani, M., & Hanzo, L. (2025). *LLM-Enhanced Space-Air-Ground-Sea Integrated Networks*. https://doi.org/10.48550/ARXIV.2509.02540

Yang, Y., & Sun, Y. (2024). Practices, Challenges, and Future of Digital Transformation in Smallholder Agriculture: Insights from a Literature Review [Review of *Practices, Challenges, and Future of Digital Transformation in Smallholder Agriculture: Insights from a Literature Review*]. *Agriculture*, *14*(12), 2193. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/agriculture14122193

Zhang, C., Zheng, X., Tao, X., Hu, C., Zhang, W., & Zhu, L. (2025). Distributed Collaborative Inference System in Next-Generation Networks and Communication. *IEEE Transactions on Cognitive Communications and Networking*, 1. https://doi.org/10.1109/tccn.2025.3527679

Zhang, H. (2024). The Impact of Fintech on The Agricultural Value Chain in Developing Countries. *Highlights in Business Economics and Management*, *40*, 1001. https://doi.org/10.54097/vge5bz30

Zhang, R., He, J., Luo, X., Niyato, D., Kang, J., Xiong, Z., Li, Y., & Sikdar, B. (2024). Toward Democratized Generative AI in Next-Generation Mobile Edge Networks. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2411.09148

Zhang, R., He, J., Luo, X., Niyato, D., Kang, J., Xiong, Z., Li, Y., & Sikdar, B. (2025). Toward Democratized Generative AI in Next-Generation Mobile Edge Networks. *IEEE Network*, 1. https://doi.org/10.1109/mnet.2025.3541078

Zhivkov, T., & Sklar, E. (2023). 5G on the Farm: Evaluating Wireless Network Capabilities for Agricultural Robotics. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2301.01600

Zhong, R., Mu, X., Jaber, M., & Liu, Y. (2024a). Enabling Distributed Generative Artificial Intelligence in 6G: Mobile Edge Generation. *IEEE Internet of Things Journal*, 1. https://doi.org/10.1109/jiot.2024.3493611

Zhong, R., Mu, X., Jaber, M., & Liu, Y. (2024b). Enabling Distributed Generative Artificial Intelligence in 6G: Mobile Edge Generation. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2409.05870