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Digital Agricultural Innovations and Rural Development: Enhancing Farmer Resilience through ICTs in Central Zambia

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Abstract
Digital agricultural innovations have been developed and adopted across sub-Saharan Africa, largely through donor-funded projects. Such projects are often insufficiently scaled as they are not based on the needs of rural communities and fail to consider local languages, cultures or infinite farmer-resource endowments. This research reports on an attempt to design a digital agriculture framework informed by participatory action research conducted in collaboration with small-scale farmers in Central Province, Zambia. It aims to complement existing agricultural business development services in the province and enable the growth of digital agriculture services throughout the community. A preliminary framework for digital agricultural innovations is proposed, and the remainder of the paper details the PAR process conducted during the two-year research to establish local needs and identify necessary requirements for digital infrastructure. The paper concludes with recommendations for future research to refine and implement the framework.

Keywords: *Digital agriculture, agricultural innovations, agricultural transformation, rural development, farmer resilience, ICTs in agriculture.*

1. Introduction

Advancement of science and technology has been a major driver of global social and economic transformations. Digital Agricultural Innovations (DAIs) the digital agriculture innovation package of artificial intelligence, big data, Internet of Things, and related revolutionary digital technologies promise huge improvements in agriculture, food security, and rural development. It is important to understand how to take advantage of DAIs to benefit the agriculture sector and rural communities.

This paper examines the adoption of Digital Agricultural Innovations in Central Zambia and its impacts. Historically, in many developing countries, agricultural production has stagnated over

decades due to lack of technological innovation, the continuous degradation of natural resources, and rapid population growth. Institutional reforms and the return of government policies designed to promote smallholder agricultural development have not succeeded in creating rapid agricultural growth. Nonetheless, it is therefore important to analyse current Digital Agricultural Innovations and rural development in Central Zambia.

Agriculture is the mainstay of Zambia's economy. Eighty-eight percent of the population of 15 million lives in rural areas and depends on agriculture and related activities for their livelihood. Like many of the other Southern African countries, in Zambia agricultural productivity is low mainly due to heavy reliance on rainfed cultivation and small-scale farmers' limited access to productive resources such as credit, quality inputs, and extension services. It has been estimated that more than 80% of all national development projects fail; in Africa, the rate is even higher (Tenywa et al., 2011). The demand for farmers to adopt new approaches has greatly increased, but most projects have failed to meet that demand; the problem is not just lack of intervention but the lack of an appropriate approach to enable the bulk of farmers to take up innovations (Shalander et al., 2017). The dynamics of increasing number of humanitarian aid agencies and changing parties in project management have added to the difficult situation. The lead author, an agronomist and socio-economist with 20 years of development project experience, decided to hire a development sociologist to analyze the problem and propose solutions.

2. The Role of ICTs in Agriculture

In recent decades, Information and Communication Technologies (ICTs) have been in use in efforts to "digitalize" agriculture and foster rural development in the lower-to-middle income countries of Africa (B.I. et al., 2013). These initiatives seek to improve the quality of rural life and the effectiveness and sustainability of rural development by reducing the costs of sharing information between citizens and agencies; enabling access to new types and sources of information; and facilitating the transfer of new skills and knowledge. This section documents different approaches to providing rural and agricultural information—and how these programs can be made both more effective and more sustainable. As more innovations are introduced, and the reach of affordable network infrastructure continues to expand, Africa is poised to realize the full potential of this transformative technology, boosting agricultural production, strengthening global and regional value chains, reducing rural poverty, creating employment, and increasing food security and nutrition (G. Ballantyne et al., 2010).

Definition of ICTs

Information and communications technologies (ICTs) are electronic information management tools, which include computers, the internet, broadcasting technologies (radio and television), and telephony systems. Mobile phones have quickly become the most persuasive ICTs in rural Africa. Governments push for digital technologies are considered effective for speeding up access to agricultural regulations, improving governance and marketing, enabling more efficient trade and boosting capacity-building; these expected outcomes contribute to empowering rural farmers in sub-Sahara Africa (Jacobus Smidt, 2018).

3. Types of ICTs Used in Agriculture

Within rural agriculture, communication processes support knowledge acquisition, reduce uncertainty and risk, facilitate networking, and extend market access. The most widely used ICTs among rural farmers are radio, television, mobile phones, and, to a lesser degree, computers, video, DVD/CD, and projectors. Radio, television, and mobile telephony facilitate the acquisition of vital development information regarding agriculture, markets, health, education, and governance. Farming systems interact extensively with data processing and analytical approaches because they generate the types of data that are best handled with ICT tools (G. Ballantyne et al., 2010). Various online data services provide access to thousands of computers worldwide without requiring hardware ownership, and cloud data centres function like utilities offering computing power when needed. Cloud storage serves as repositories for shared datasets accessible to all users, enabling instant access, analysis, and interpretation of information. Adaptive agents, sensors, RFID tags, and numerous connected devices are redefining agricultural practices, behaviour, information flows, and stakeholder interactions. ICTs reinforce market engagement and support the sustainable use of agricultural resources; however, such applications have yet to become widespread among small, resource-poor farmers in developing countries (Sikalumbi, 2022).

4. Farmer Resilience: Definition and Importance

Within the agriculture sector, constantly evolving and innovative digital tools reshape agriculture, rural development, and sustainability in the region of Central Zambia, a key breadbasket lost to urbanization and climate change. Reliable digital innovations encourage higher yields and foster farmer resilience to climate change and market dynamics imposed by urban conurbations. In this leadership role, farmer connectivity to a broad range of digital tools supports the transformation of agricultural practices in these rural landscapes (Sikalumbi, 2021). The Region of Central Zambia Central Zambia represents the breadbasket of the region (Maru & Tafuna'I, 2018). In the context of rapid population and urban growth, enhancing small-scale and subsistence farming becomes key for regional food security, economic development and poverty reduction, particularly around Monze and Choma. Digital solutions such as e-commerce provide farmers with direct access to buyers and fair prices. Digital payment platforms enable cashless transactions and prompt cash-flow, while weather and climate information services facilitate agro-advisories and crop insurance. Digital agriculture also encompasses the collection and analysis of data on soil, weather, and pests, enabling better decision-making, increased productivity, and risk reduction.

Agricultural Innovations in Central Zambia: Agricultural productivity, once traditionally rooted in knowledge transfer through formal extension services within Central Zambia, now thrives on digital innovations increasingly embedded in rural development efforts in the form of ICTs. Several governments of developing countries, including Zambia, recently renewed the political priority given to agricultural development along with the objective of enhancing farmer resilience and food security. In Central Zambia, digital agricultural innovations enable the introduction of new production and marketing methods to increase agricultural yields, reduce risks, and counter

the negative effects of ageing and brain drain and migration. Improved digital infrastructure, read by innovative mobile technologies, is increasingly driving business models designed to help farmers, particularly smallholders, gain access to vulnerable markets (G. Ballantyne & Chavez-Tafur, 2019). The ability of digital agriculture to enhance rural development therefore appears as a crucial link to analyse the sector's ability to guide the economic transformation of the region.

5. Challenges Faced by Farmers in Central Zambia

Farmers in central Zambia experience several challenges relating to post-harvest handling, weather patterns, market prices, input costs and access to storage facilities for their harvests (Novas Somanje, 2015). Surveys conducted in the Central Province during 2015 and 2016 reported that nearly 40% of the small-scale farmers interviewed were obliged to sell their produce immediately after harvesting due to lacking access to storage facilities. Over two thirds of the small and medium-scale farmers surveyed indicated that storage issues were affecting them quarterly or frequently and suggested improvements in transportation and market access as effective solutions.

These agricultural challenges are compounded and exacerbated by climate change impacts and variability, which are increasing in the region in the form of floods, drought, increased temperatures, shifting seasons and alterations in rainfall (Sikalumbi, 2021). Chilanga District, which falls within the Central Province, is particularly vulnerable to climate variability due to its dependence on rainfall for agricultural systems (Kinkese, 2017). Drought poses the most significant threat to crop yields, especially for maize, and is a direct result of climate change, creating a strong case for the deployment of readily accessible climate-smart and enhanced conservation agricultural techniques.

Climate Change Impacts

Climate change poses a significant threat to agricultural productivity and food security in Zambia, making adaptation essential. These threats are particularly severe during the growing season, when variations in rainfall more profoundly disrupt maize cultivation than do mean temperature changes or rising CO2. According to various climate scenarios, Mokambo receives the lowest projected rainfall by 2030, with anticipated increases in temperature and drought intensity continuing until 2050. Farmers must therefore adopt measures that enhance the resilience of food crops and cash crops such as cassava, zucchini, sweet potatoes, maize, and peppers to shifting climatic conditions. Ensuring the availability of water for irrigation throughout the year is critical to address food insecurity in the area (Novas Somanje, 2015; Kinkese, 2017).

Market Access Issues

Market access poses challenges for smallholder agriculture in Central Zambia, impacting participation and productivity. Enhancing market linkages through informal trade groups and mobile technology can positively influence marketing decisions. Agricultural commercialisation and input supply strategies are vital for improving access. Addressing these issues requires

exploring policy options, developing infrastructure, and promoting rural market networks. The creation of commodity exchanges was delayed by political issues, with the Warehousing Licensing Authority starting only in 2017. Smallholder farmers dominate the market, necessitating substantial sensitisation. The lack of solid agricultural policies undermines market confidence, and limited financial participation from banks affects governance. The World Bank aids innovative financial products for agriculture, including warehouse receipt financing, credit guarantees, insurance, and hedging. Promoting digital solutions like mobile banking has enhanced financial inclusion, supported by government initiatives to boost digital usage. The Bank of Zambia adjusted transaction limits to stimulate digital transactions (Musitini et al., 2019; Siwale, 2019).

Resource Limitations

Agricultural development in developing countries, particularly in Sub-Sahara Africa like Zambia, is often restricted by limited resources, household assets, and inadequate information regarding agricultural inputs and market changes. The development of agriculture correlates with financial development; as financial infrastructure improves, so does agricultural productivity. Financial services such as credit, savings, insurance, and payments are vital as they provide necessary funds for investment in technology and inputs. Resource-poor smallholder farmers are particularly affected due to their inability to directly borrow from financial institutions, which limits their access to modern agricultural methods. This financial constraint hampers the introduction of technology and input use in farming. Enhancing the agricultural sector can alleviate rural poverty and bolster food security in countries where agriculture is the primary livelihood. The adoption of agricultural technologies relies heavily on access to finance for purchasing seeds, fertilizers, and equipment. Though informal rural financial service providers in Zambia offer small amounts of credit, it is often insufficient for substantial agricultural investment (Siwale, 2019).

6. Digital Solutions for Enhancing Farmer Resilience

Resilience is a business focus across the region, with resilience-building solutions featuring extensively on local and government agendas. Enhancing resilience in rural economic activities is a pertinent topic for development actors, international organizations, NGOs, and private investors. Their inquiries towards HAIL seek to understand how digital solutions can contribute to strengthening resilience (G. Ballantyne & Chavez-Tafur, 2019).

The principal constraints to economic growth in rural central-zambian economies—such as insufficient and unstable production, widespread deforestation, inadequate access to finance, and low levels of educational capital—are not alleviated by isolated improvements to upstream or downstream discovery processes; rather, they stem from a more systemic failure. Achieving 'mechanical resilience,' in the sense of a system that operates smoothly unless an intervention points out specific corrections, requires a deeper, systemic approach.

Mobile Applications for Information Access

Mobile applications for information access are crucial for enhancing agricultural practices and market connectivity in Africa. Studies show that mobile phones positively impact markets and economic development, especially in rural areas. Mobile technology facilitates information exchange, improves governance, and supports distance learning and emergency systems. Various research methods highlight the significance of mobile solutions in agriculture. There is significant growth in mobile communication and application deployment across sub-Saharan Africa, aiding policy-making and farming practices. Effective IT use must align with rural realities, which often include widespread illiteracy and limited extension services. Initiatives like the African Cashew Initiative equip farmers with IT-based pricing systems updated via mobile. Uganda's Lifelong Learning for Farmers program provides agricultural info via interactive SMS. In Niger, mobile phones communicate product prices directly to farmers. The iCow initiative in Kenya employs text messages and videos for cattle management. Video interventions, such as Digital Green's efforts in India, transfer agricultural knowledge and boost productivity. In Bangladesh, farmer learning videos disseminate quality information widely, with distribution being key for success. Video learning, alongside media like radio and television, enhances agricultural extension. Open-air video presentations foster unsupervised learning, creativity, and group cohesion among rural populations, including women, youth, and the poor (Gichamba & A. Lukandu, 2012; Sousa et al., 2019; Sikalumbi, 2023).

E-commerce Platforms for Market Access

The stakes for smallholders to access better markets are increasing in Zambia. Several platforms support agricultural markets, ranging from e-commerce, tailored SMS services, and specialized supply chains for niche products. The most ambitious platform is AgriPredict, which connects farmers and buyers. The company collects information to help clients better plan cultivation and estimate yields. A service allows third-party suppliers to track and generate reports on crop cultivation using satellite data and agricultural inputs, enabling the identification of fraud and better management of their supply chains by companies such as Yara or Animal Sciences. The platform also allows buyers to engage in contracts before the season starts to pre-purchase harvests and monitor farms during the season, reducing risks of shortfalls and better planning marketing.

Due to potentially high costs and connectivity requirements, the app serves primarily exporters, warehouse managers, and large input suppliers, rather than individual farmers or farm organizations. The platform is currently optimized for maize, rice, and soya, with plans to include other crops in future iterations.

Remote Sensing and Data Analytics

Agricultural systems worldwide fundamentally depend on land resources. Mapping agricultural areas, such as apiculture systems, enables evaluation of their temporal development and relationship to climatic and other factors. However, quantifying changes in crop types in heterogeneous fields over time requires simplified land-use categories, complicating assessment.

Changes preferably are tracked using indicators. Statistical data typically pertains to administrative units, and it is difficult to spatially link to high-resolution land-cover classes because most countries report only total values for crop groups, not individual types. Earth observation (EO) imagery at medium spatial resolutions, acquired since the early 1980s, has provided a valuable record of detailed land cover at local scales (Duro, 2012). Scientists and practitioners have explored methods of combining EO imagery and census data using various techniques. Land-cover information from sensors such as SPOT-4/VEGETATION and AVHRR have been used to construct refined land-use maps at scales better suited for agricultural statistics and rural development. Dasymetric and volume-preserving techniques have been applied to relate coarse census data to higher-resolution raster products. More recent approaches employ finer-resolution land-cover maps to spatially constrain datasets, resulting in explicit databases suitable for modeling ecological responses of agricultural landscapes and assessing tradeoffs in agricultural development. Complementary to land-use reporting, an indicator capable of quantifying crop-type changes relative to surface characteristics derived from satellite data would address uncertainties in long-term agricultural change (Tonneau et al., 2019).

7. Case Studies of Successful ICT Implementation

Some ICT initiatives in rural settings show promises of increasing sustainable productivity and market opportunities. The Electronic Uganda National Innovations Systems (EUNAIS), developed in 2009, linked smallholder farmers in Western Uganda with technical experts to provide advice on upgrading farm production skills (Shepherd, 2018). Farmers also were trained to develop content in local languages and manage websites, a capability that might add value to other applications intended to serve people in rural communities. The system enabled farmers calling the centre to follow automated voice prompts to choose the language and leave messages requesting information on any agricultural topic; responses were supplied by experts. Low usage partly was attributed to widespread illiteracy, combined with farmers' hesitancy about using technology for certain activities, despite having already embraced mobile phones. Farmers were especially reluctant to attempt to sell products via the service, preferring traditional meetings with buyers in local markets. The costs of EUNAIS proved too high. Without evident government buy-in, foreign donors were reluctant to offer further funding.

ICT-enabled knowledge sharing in agriculture may present opportunities to improve access to information and services and strengthen two-way communication between stakeholders (Yadav, 2011). Stakeholders may obtain access to better tools for transfer of skills and knowledge to the wider community, thereby amplifying the impact of ICT-enabled initiatives, as reported for e-Krishi Meta Portal in the Indian Himalayas, Edukart Internet Portal of Himalayan College of Agricultural Sciences & Technology, and Himalayan Crop Database. Various transition and developing countries apply ICT such as eLIS, locally developed web- and mobile-based ICT, portal packages, and Radio and Audio on Demand to facilitate sharing of agricultural knowledge and expediting adoption of new technologies and practices. Such initiatives easily may be scaled up to other regions, with provision for appropriate language support and according needs assessments.

Case Study 1: Mobile Weather Forecasting

Modelling and forecasting systems now routinely generate daily weather predictions for the next 10 days, enabling the incorporation of meteorological information into crop simulation models to facilitate the development of strategies for adapting to climate risks (Gebru et al., 2018). Interface requirements for such systems include the use of mobile phones, support for irrigation scheduling, minimization of input data demands, the acquisition of meteorological input from remote weather stations connected via satellite, provision of farmer-specific, location-relevant forecasts, early warning of potentially damaging events, and free access for smallholders. Internet platforms are therefore able to exploit weather simulation and forecasting to offer services that enhance the decision-making process linked to climate-sensitive sectors such as agriculture.

Case Study 2: Digital Payment Systems

Mobile money services have transformed the financial sector in several parts of Africa, making monetary transactions simpler, quicker, and more secure. Kenya stands out as a leader in this transition. Safaricom's mobile service, M-PESA, launched in 2007, enables users to deposit, withdraw, and transfer money using cellular phones. By 2009, M-PESA accounted for billions of shillings in transactions, roughly 10 per cent of Kenya's GDP. People use mobile money primarily as a cash transfer system and for storage and savings. Most transactions are transfers from urban to rural areas. M-PESA has expanded access to financial services, with more than half the estimated 8.5 million customers previously unbanked. Several studies document increased transfer volume and frequency, significant substitution for other monetary instruments, and effects on trajectories of economic change (Batista & C. Vicente, 2013).

8. Government Policies and Support for Digital Innovations

Government policies and support play a vital role in fostering digital innovations in agriculture. Agricultural innovation systems that engage a broad spectrum of privatesector firms and farmers in production, contracting, sourcing, and marketing drive growth, diversification, and poverty reduction (Adwoa Onumah et al., 2023). Farmer-led innovations in agricultural mechanization stimulate on-farm activities, value addition, agri-business, agricultural start-ups, and youth participation. Mobilizing stakeholders to generate systemic frameworks for the control of avian influenza and the development of smallholder livestock production enhances food security. The development, documentation, and dissemination of farmer-based innovations improve adoption and diffusion efforts and address the needs and practicalities in agro-pastoral communities.

Non-farm activities like petty trading, charcoal burning, and car mechanics contribute to income diversification and poverty reduction. Linking smallholder farmers to national agricultural trade networks boosts market participation and entrepreneurship. Although Internet access is limited, mobile phones and digital technologies greatly assist communication, market information access, vaccination tracking, and financial connections. Internet technology enhances agricultural efficiency and market reach. Countries gain from technology hubs that support agriculture and empower rural innovators. Effective policy development must balance technology and institutional change; without strong institutions, new technologies cannot transform agriculture

or alleviate poverty. A comprehensive approach is essential, focusing on technology generation, adoption, and use. Empirical studies highlight the need to integrate innovation systems with value chain analysis, moving beyond traditional agricultural methods. The main challenge for policymakers is designing supportive policies that foster coordination and innovative systems evolution (Resnick & Thurlow, 2008).

9. Partnerships and Collaborations in ICT Development

Access to affordable and reliable ICTs in rural areas poses a challenge in many developing countries, especially in Africa, where infrastructure, connectivity, and cost issues prevail. As a result, most communities lack internet access, though many have radio communication. Additionally, digital information is often produced by and for Global North, creating an engagement barrier. Establishing partnerships for scalable ICT solutions in rural areas is essential, yet difficult due to varying organizational cultures and resource gaps. Worldwide conferences emphasize the importance of digital technologies in agriculture, but rural regions like Zambia still face inadequate voice and data infrastructure, with unreliable connectivity. Overcoming these challenges necessitates investments and collaboration around open standards. Local entrepreneurs, including telephone line operators, often gather and manage rural data using low-cost open wireless equipment. Some well-funded mobile and internet providers also offer access, perceived as innovative efforts to foster development and competition in these areas. (G. Ballantyne et al., 2010) (Malambo et al.2023)

NGOs and Community-Based Organizations

Non-Governmental Organizations (NGOs) and local community-based organizations form the backbone of development assistance and rural services in Central Province, Zambia. NGOs often work in partnerships with a diverse range of international agencies that provide either financial support or program guidance for development initiatives. Central Province hosts several not-for-profit professional associations that champion biodiversity conservation, human rights, indigenous medical knowledge, women's rights, and gender equity. Many of these organizations were established in the early 1990s during Zambia's transition to multi-party democratic rule and the phased liberalization of its economy (Mazvimavi et al., 2011). A considerable number of NGOs are devoted to enhancing rural development outcomes by improving water, sanitation, improvement, and food security. Agricultural extension services and livelihood promotion programs are often entirely dependent on NGO oversight.

Private Sector Involvement

There are various private-sector initiatives to foster digital innovation in the rural commercial and agricultural spheres. Input may be directly provided, or products and services can be facilitated. Mobile network operators play a particularly important role. These provide communication services and mobile money (such as telecash) that enable workers in the informal incipient urban labor market to find agricultural employment in the form of casual labor. Ongoza, a local company, provides telecommunication and related services from a fixed location within

the settlements on the outskirts of development areas. AgriWallet, a startup, makes digital payments between companies and farmers and agricultural mechanization services using urban workers to operate the machinery, thereby extending the rural economy into agriculture and its continued growth and innovation into agribusiness. Picme and Tweetfinity are early-stage startups engaged in the agricultural value chain, and Babban Gona, an external financing and marketing company with a virtual parent company that acts as a franchisee, is expanding into the area (Siwale, 2019).

10. Barriers to Digital Adoption among Farmers

Numerous barriers constrain the adoption of digital technologies by smallholder farmers. Inadequate ICT literacy impedes procurement and usage of electronic devices and digital platforms. Financial burdens limit capacity to secure requisite hardware, software, and internet access. Traditional social networks offer free advice, acting as an alternative to paid digital services for some farmers. Access to training and formal support is very limited, so that many farmers are reluctant to adopt unfamiliar technologies. Older, more experienced farmers are frequently disadvantaged relative to younger counterparts, highlighting the importance of age as a moderating variable. Limited literacy and technical skills also restrict comprehension of complex weather forecasts. Financing saving, narrative-driven recommendations and training programmes can overcome barriers, promote widespread uptake and empower farmers in decision-making processes (Precious Alant & Ojo Bakare, 2021).

Technological Literacy

As digital solutions play an increasingly crucial role in agricultural development, the ability to understand their use becomes fundamental. Agricultural productivity can benefit from innovative financial and market instruments. Equally important are digital platforms for e-commerce, enabling farmers to access information and interact with other actors in the value chain. Yet, the benefits from digital innovations depend on the capabilities of farmers to effectively utilize them, and such capabilities remain limited among rural populations. High illiteracy rates (Precious Alant & Ojo Bakare, 2021) impede farmers' awareness of the implications of digital innovations, raising questions about their ability to identify the most relevant solutions or negotiate their terms of use, thereby limiting the scope of the benefits.

Digital development therefore involves the conquest of new territories that must be accompanied by the appropriation of tools and the construction of collective learning. Strengthening digital skills becomes a prerequisite for complementing and widening the scope of basic skills. More generally, it offers an opportunity for upward social mobility, including for the farmers themselves. Developing relevant digital content and systems of information and collective learning adapted to the level of users therefore emerges as a key priority.

Reinventing brokering mechanisms Brokering agricultural information consistently emerges as a core activity in the digitalization of agricultural value chains.

Infrastructure Challenges

Smallholder farmers (SHFs) in Central Province produce 55 percent of the maize. Other frequently grown crops are cotton, groundnuts, sunflower and soya beans. The most important poultry species are chickens and guinea fowl, and most of the draft power is provided by oxen. Agriculture is primarily rainfed, and just 5–10 per cent of cultivated land is irrigated. The main sources of income for SHFs are sale of livestock and livestock products, cropping, off-farm and petty trade.

SHFs face a growing number of challenges in agriculture, especially access to finance options and agricultural knowledge. Yet good access to credit is important for financing key hardware, including irrigation systems, and for farm input purchases. Loans also enable SHFs to scale out and increase production during good seasons, and to finance their off-farm activities when agricultural output falls during droughts or growing-season shocks (Siwale, 2019).

Policy barriers and market failures corner SHFs and push them into a chronic cycle of poverty (Moyo et al., 2017). The low usage of mechanical power and the limited use of organic and inorganic fertilizer both limit agricultural productivity, while tradable surpluses are often wasted due to inadequate storage and high post-harvest losses. The greatest infrastructural obstacle to improved market access and trade is the poor existing rural roads network, the majority of which are gravel and earth roads.

11. Future Trends in Digital Agriculture

The adoption of satellite-based technologies is anticipated to become more affordable, likely making Digital Agriculture more accessible to small-scale farmers. While not all farming operations will implement digital systems, those that do are expected to gain a competitive edge. Technologies such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) are poised to play significant roles in industry growth. Digital Agriculture is likely to become dominated by large international suppliers offering comprehensive digital-affinity services compatible with various hardware vendors, potentially creating barriers for smaller vendors (Lemeilleur et al., 2019).

Emerging data-driven models will be integral to Digital Agriculture, generating actionable knowledge beyond current modeling capabilities. However, such models inherently amplify existing inequities. Low-income countries often remain uncovered by these services, exacerbating the ''data divide'' between developed and developing regions and between large and small-scale farmers. Platforms like PlanetWatchers specialize in real-time agricultural intelligence for large-scale operations, while application growth for smallholders in developing economies remains modest.

Private sector engagement complements these trends. Start-ups worldwide offer solutions connecting farmers to credit, information, and markets, exemplified by entities such as JAMI (Senegal), FARMCROWDY (Nigeria), TROTRO Tractor (Ghana), iarata (Kenya), and Hello Tractor (Nigeria). These innovations address longstanding issues of fragmentary (small, dispersed) markets and information asymmetries. Synthetic and digital biology, including gene

editing and synthetic fertilizers, represent additional avenues to address agricultural sustainability. Although such technologies are not yet mature, several methods have already been harnessed in agricultural biotechnology and may transition into practical solutions for farmers and consumers (Kremer Sott et al., 2021).

Artificial Intelligence Applications

Agricultural producers in developing economies often rely on experience-based or trial-and-error techniques to make decisions regarding their crops. This approach can lead to uncertainty and errors, both of which result in decreased productivity and profitability. Fortunately, the increased availability of affordable digital technology, mobile connectivity, and on-demand ship-hailing presents an innovative and collaborative opportunity for cost-effective solutions that can augment the work of these producers and improve the livelihoods of smallholder farmers and rural communities.

Artificial intelligence (AI) offers significant opportunities to enhance agricultural productivity and income for rural communities in Central Africa, where agriculture accounts for 85% of employment. AI can facilitate sustainable innovations that aid farmers and stakeholders in the agri-food chain. These AI innovations serve as a cost-effective alternative to purchasing traditional agricultural equipment, allowing smallholder farmers access to efficient digital technologies. However, addressing issues like poor crop yields requires a comprehensive approach that considers potential side effects. Developers must also tackle challenges such as monopolies on data, seeds, and pesticides to ensure equitable solutions, preventing a widening gap between countries that dominate agricultural and data technology and those that do not. (Gwagwa et al., 2021)

Blockchain for Supply Chain Transparency

The tracking of agricultural products along the value chain remains an open challenge in several applications (Kamilaris et al., 2018). When a product travels through several regions, often multiple transport companies are involved. This increases risk and can result in lost or mislabeled shipments. Within the supply chain, trust among stakeholders is paramount. Cost-effective technologies for anti-counterfeit and traceability are therefore of paramount interest. Due in part to their intrinsic cryptographic features and support for distributed consensus mechanisms, blockchain technologies can support fruit and vegetable supply chains at critical points such as handling and loading. Blockchain is an effective distributed digital ledger of immutable transactions that run based on cryptographic proof, eliminating the need for a central authority, and supports smart contracts and token exchange on a peer-to-peer basis. The combination of distributed consensus mechanisms and key blockchain properties, immutability, transparency, fault tolerance, and robustness—is of particular interest for supply chains.

12. Impact Assessment of ICTs on Rural Development

Central Zambia, like many rural communities, faces numerous development challenges that can be addressed through innovative information and communication technologies (ICTs).

Methodological approaches in the region assess the effectiveness of digital agricultural innovations for rural development, employing a questionnaire developed through pilot research in Kabwe, Zambia. The questionnaire measures the impact of digital agricultural tools and services on farmers' access to information and subsequent development (Yadav, 2011).
Zambia, a landlocked country in Southern Africa, continues to experience hardships related to rural underdevelopment despite the presence of diverse agricultural innovations for community development. Notably, digital farming platforms such as MTI's Msokoto and iShamba provide farmers with advice across various topics, with many local sites actively engaging in agricultural development (B.I. et al., 2013). By allowing granular consideration of the impact of digital agricultural innovations, including interactive case studies, future assessments can more thoroughly evaluate the role of such innovations in rural development.

Economic Impacts

Zambia emphasizes maize research to enhance growth and reduce poverty, as rural poverty is prevalent and maize is a key income source and staple food. Investments in maize productivity are crucial for improving incomes and food consumption among poor rural households. Consequently, multiple donor-supported projects have been launched to promote improved maize technologies, necessitating evaluations of their impacts to guide policy makers and future investment proposals. The agricultural sector is vital for Zambia's economic development, contributing significantly to GDP, employment, food supply, and raw materials for various industries. Despite its importance, the sector's output remains low due to inadequate inputs, perpetuating the low-income conditions for many rural inhabitants dependent on agriculture. Maize, alongside rice, wheat, and sugarcane, is among the major crops cultivated. Its production significantly influences the economy, contributing a higher percentage to agricultural output and being the main staple for urban and rural Zambians. (A. Howard et al., 1970; Siwale, 2019)

Social Impacts

Through the digital innovations employed at the provincial e-information centers established in Central Zambia under the Regional Agricultural Policy and in collaboration with the government and private sector (see Appendix 1), along with the interlinkages they have established with other information stakeholders, several direct impacts on the rural environment have been observed. Firstly, there is the obvious impact of generating rural employment. Operators are required at the zone and district levels, receiving regular salaries and often engaging family members as part-time employees to assist with daily e-mail communication services. Secondly, every household capable of meeting the subscription and communication costs benefits from the service by gaining a voice channel to influence broader policy developments. Lastly, the availability of voice communication via these satellites assists in the circulation of specific information at the target level, such as in organizing communal work on social infrastructure. Similar activities were reported in major floods and droughts during the 1990s . Nonetheless, the data do not provide sufficient insight into how farmers utilize this service; the focus has been on establishing

communication infrastructure and identifying the determinants of personal communication demand (Yadav, 2011).

13. Conclusion

The preceding sections have scrutinised digital agricultural innovations in their multifaceted interaction with rural development and the mitigation of land degradation and other vulnerabilities in central Zambia. The use of centre-pivot (CP) irrigation systems in newly created settlements such as Mwomboshi demonstrates that up to 200 hectares can be effectively cultivated by a handful of farmers using state-of-the-art digital technologies. The excessive establishment of farms in watersheds and on fragile slopes (sometimes exceeding a hundred hectares) warrants additional research into pragmatic strategies that encompass agronomic practices, policies, and governance within a systemic framework. To reconcile the development of large farms with the maintenance of essential ecosystem services, substantial support in irrigation management is imperative. For example, state services could ensure guaranteed water availability and distribution, while a national agency might assume responsibility for gravimetric surveys addressing geophysical aspects (Jacobus Smidt, 2018).

Recommendations for Policy Makers

Policy makers in Zambia should adapt the agricultural legal framework for digitalisation, collaborating with the telecommunications regulatory authority to ease the restrictive zero-rating policy on internet access. The government must promote institutional development and create policies to build confidence among agriculture stakeholders to enhance trading and encourage bank equity participation. Reducing collateral requirements for smallholder farmers and harmonizing loan procedures is essential for accessing affordable financing. Collaborating with banks to support smallholder farmers' debt and minimizing credit risk is crucial. Implementing Landholding Certificates, like ParcelCerts, would provide legal proof of ownership and enable farmers to secure credit. Revising rural farmer cooperatives can improve information flow, education, and address specific constraints. Banks and microfinance institutions should promote awareness of financial products and government programs like the Zambia Credit Guarantee Scheme. Enhancing financial inclusion through private sector initiatives will boost access to finance, agricultural productivity, and food security. Improving credit access permits farmers to buy inputs, reducing reliance on subsidies, lowering poverty, and facilitating investment in infrastructure. The Zambian Government has identified policy challenges affecting digital agricultural innovation for rural development in the 2012–2030 National Agriculture Policy, including climate variability, inadequate services, poor policy implementation, limited market access, and low productivity. The policy focuses on crop diversification and conservation agriculture to address climate change impacts, employing methods such as crop rotation and

minimum tillage to enhance soil health and mitigate land degradation. (Siwale, 2019; Kinkese, 2017)

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