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Comparative analysis of agricultural extension models in the United States, Rwanda, and Nigeria: Innovations in capacity building, technology integration, and educator preparation

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ABSTRACT

Agricultural extension services are crucial in enhancing farmer education, increasing agricultural productivity, and promoting sustainable farming practices worldwide. This concept paper examines the agricultural extension models in the United States, Rwanda, and Nigeria, focusing on capacity building, technology integration, and educator preparation. The US model, rooted in the cooperative extension system, integrates land-grant universities, advanced digital tools, and structured educator training. Rwanda's Twigire Muhinzi model emphasizes community-led extension, leveraging farmer promoters and information and communication technology (ICT) driven advisory services. Nigeria's extension system adopts a public-private partnership approach, incorporating ICT tools, decentralized extension services, and farmer support schemes such as the growth enhancement support scheme. The study identifies common themes and challenges across the three systems, including scalability issues, regional disparities, funding constraints, and the digital divide. Findings suggest that no single extension model is universally applicable; rather, successful systems must be context-specific, participatory, technology-driven and adaptable to meet the needs of their stakeholders. The study recommends cross-country collaboration, enhanced digital literacy, and policy alignment to improve extension effectiveness. By integrating best practices from each system, agricultural extension services can be more inclusive, responsive, and sustainable, ultimately strengthening global food security and rural livelihoods.

Keywords: agricultural extension, capacity building, technology integration, educator preparation, cooperative extension, ICT in agriculture, public-private partnerships

INTRODUCTION

Agricultural extension systems are critical in addressing the challenges of food security, rural development, sustainable farming practices, and climate resilience. Extension services act as a bridge between research institutions, policymakers, and farmers, facilitating knowledge transfer, innovations, and practices to improve agricultural productivity and resilience (Anderson & Feder, 2007; Prince et al., 2023). Through agricultural extension, farmers gain access to essential information on pest management, crop diversification, irrigation techniques, and market dynamics. Agricultural extension systems are pivotal in addressing the needs of smallholder farmers, who form the backbone of global agriculture. In the US agriculture, food, and related industries contributed approximately 5.5% to the US gross domestic product (GDP) in 2023 and provided 10.4% of the US employment in 2022 (United States Department of Agriculture, Economic Research Service [USDA ERS], 2025). In Nigeria, agriculture contributes to 25% of the nation's GDP, 70% of the labor force, and 66% of the working population. In Rwanda, agriculture accounts for approximately 29% of total GDP, contributes significantly to national export earnings, and employs over 60% of the population (Food and Agriculture Organization of the United Nations [FAO], 2020; United States Department of Agriculture, National Institute of Food and Agriculture [USDA NIFA], 2025).

These farmers often face significant challenges, including limited access to inputs, markets, and information, making effective extension services essential for improving the livelihoods of farmers, and thus improving food security (Adetayo & Eunice, 2013; Gwary et al., 2015). Effective extension systems also serve as a platform for integrating research with practice, to ensure that the latest agricultural innovations are not confined to laboratories but are adapted to the specific needs of diverse farming communities. For instance, technology transfer initiatives in the US, such as precision farming, rely on extension agents to train farmers in optimizing resources and improving yield (USDA NIFA, 2025).

Table 1. Extension systems and primary funding sources in the United States, Rwanda, and Nigeria

Country	Extension system	Sources of funding
United States	CES with land-grant universities	Federal, state, and county governments; land-grant universities; grants; philanthropic funds
Rwanda	Twigire Muhinzi model with farmer promoters, FFS, and decentralized, community-led extension	Government funding through the Ministry of Agriculture; donor agencies; NGOs; international partners
Nigeria	PPP model with government agencies, NGOs, private sector, and decentralized local offices	Federal and state governments; international donors; private sector investments; development programs

This concept paper examines the agricultural extension models in the United States, Rwanda, and Nigeria, focusing on capacity building, technology integration, and educator preparation. By examining the strengths and challenges of various extension models, this study provides insights into designing extension systems that are inclusive, participatory, and sustainable. In this study, we highlight the evolution of extension services in these three countries, and how they address local needs while tackling global challenges. This study explores the cases of the United States, Rwanda, and Nigeria and their distinctive approaches to agricultural extension. The selection of the United States, Rwanda, and Nigeria for this study is driven by the professional and academic backgrounds of the researchers involved. Each researcher has direct ties to these countries, either as a native or through their work as extension personnel, or study experiences. This unique perspective allows for a deeply contextualized comparative analysis of agricultural extension models, as the researchers know firsthand the institutional frameworks, challenges, and opportunities within each system.

The US system is grounded in the land-grant university tradition, which emphasizes research, education, and extension through decentralized structures and advanced technology (Association of Public and Land-Grant Universities [APLU], 2012; Ding, 2015). This method comes with diversified funding mechanisms at the local, state, and federal levels, partnerships with land-grant universities, and is built upon both the technical and practical education of the extension agents. Digital tools and online resources tailored to training programs further enhance their outreach and efficiency.

Rwanda's agricultural extension services, on the other hand, are intricately tied to national development priorities. Rwanda's agricultural extension services integrate community-based extension approaches with modern technology, to leverage cultural frameworks and build trust among farmers and stakeholders (Rwanda Governance Board [RGB], 2022; Uwimbabazi, 2012). Frameworks such as Umuganda, a traditional practice of community service on the last Saturday of the month, have been utilized to encourage collective farming and knowledge-sharing initiatives (Flinkenflogel et al., 2015). Rwanda's emphasis on smallholder farmers and the integration of information and communication technology (ICT) tools such as mobile apps and animated videos highlight its innovative and inclusive approach to extension services (Mugabo et al., 2025). On the other hand, Nigeria's agricultural extension system has evolved into a public-private partnership (PPP) model, integrating government agencies, non-governmental organizations (NGOs), international donors, and private sector investments to enhance knowledge dissemination and agricultural productivity (Adebayo, 2004; Aina et al., 2019; Arowosegbe et al., 2024; Bisseleua et al., 2018; Ifeanyi-Obi & Corbon, 2023).

Since the early 2000s, PPP-driven extension models have dominated, incorporating ICT tools to improve farmer access to agricultural inputs and advisory services. The growth enhancement support scheme (GESS) introduced e-wallet systems, enabling farmers to receive subsidized inputs via mobile phones (Adesina, 2012; Aina et al., 2019; Arowosegbe et al., 2024; Bisseleua et al., 2018; Ifeanyi-Obi & Corbon, 2023; Owolabi & Yekinni, 2022). Digital tools such as radio, television programs, and social media platforms like WhatsApp and Facebook have enhanced extension outreach (Ifeanyi-Obi & Corbon, 2023; Oladele, 2011). Despite these advancements, funding disparities, regional differences, and digital illiteracy remain challenges (Arowosegbe et al., 2024; Onyia, 2021; Owolabi & Yekinni, 2022; Shehu, 2018). **Table 1** compares the Extension structure and funding resources in the United States, Rwanda, and Nigeria.

AGRICULTURAL EXTENSION SYSTEMS

The US Extension System

The US agricultural extension system is one of the most established and comprehensive in the world. Rooted in the land-grant university model established by the Morrill act of 1862, the system integrates research, education, and extension services to address the needs of rural and agricultural communities (Sorber et al., 2019). The Morrill act of 1862 laid the foundation for land-grant universities, tasked to provide education in agriculture, science, and engineering to support rural development (Williams & Muchena, 1991). The Hatch act of 1887 further advanced this mission by funding agricultural experiment stations to conduct research tailored to local farming needs. Finally, the Smith-Lever act of 1914 institutionalized the cooperative extension system (CES), mandating land-grant universities to disseminate research-based knowledge directly to farmers and rural communities (APLU, 2012; Ding, 2015).

The CES operates through a tripartite partnership between federal, state, and county governments. The USDA provides guidance and funding, while state and land-grant universities develop region-specific programs. Local extension offices act as the operational units, delivering tailored services to diverse agricultural communities. Extension agents, affiliated with land-grant universities, play a crucial role in transferring knowledge and innovations from research institutions to farmers, ensuring flexibility and responsiveness to both regional and national agricultural challenges (APLU, 2012; Caillouet, 2022). The US extension service has four primary program areas, agricultural and natural resources, 4-H youth development, health and human services, and

community development. This paper will focus on the agricultural and natural resources program area, as the other program areas do not have equivalents in Nigerian or Rwandan extension services.

Role of technology and educators in the US extension system

The evolution of agricultural extension in these countries has progressed from printed materials and face-to-face interactions (early 20th century) to radio, television, and computer-based tools. The Internet, mobile apps, artificial intelligence (AI), and precision agriculture have since transformed extension services, making them more accessible, data-driven, and efficient for farmers nationwide (Xu et al., 2023). Technology has been a cornerstone of the US agricultural extension system, enabling efficient and effective knowledge dissemination. Precision agriculture, remote sensing, and geographic information systems (GIS) are widely used to optimize resource use and increase productivity. For example, extension agents provide farmers with data-driven recommendations on irrigation scheduling, pest control, and crop management (Ding, 2015). Digital tools such as mobile applications such as WhatsApp, text messages, webinars, and online learning platforms have expanded the reach of extension services. These technologies allow farmers in remote areas to access expert advice and training without the need for physical interaction. During the COVID-19 pandemic, virtual extension services became a critical resource, demonstrating the system's adaptability and resilience (APLU, 2021). The US CES has increasingly embraced digital technologies to enhance agricultural productivity and sustainability, with a particular emphasis on expanding the use of digital tools for educational outreach. Online learning platforms and virtual events have become integral components of this shift, a transformation that was notably accelerated by the COVID-19 pandemic, which highlighted the need for remote learning solutions (Fawcett et al., 2020; Greene et al., 2020; Mancuso et al., 2023).

In parallel, another significant trend is the growing adoption of precision agriculture technologies, such as gobal positioning system-guided equipment, remote sensing, and data analytics (McFadden et al., 2023; USDA NIFA, 2023). These technologies empower farmers to manage crops and livestock with unprecedented accuracy and efficiency. Extension agents have worked diligently to integrate data analytics into decision-making processes, allowing them to offer more personalized, targeted advice to farmers and other stakeholders (USDA NIFA, 2023). Furthermore, the CES is exploring the potential of AI and machine learning to further improve productivity and decision-making (Prestegaard-Wilson & Vitale, 2024). This data-driven approach not only enhances the effectiveness of Extension programs but also ensures their relevance in addressing pressing contemporary challenges, such as climate change and food security.

Educators play a central role in the US extension system, serving as the link between research institutions and farming communities. Their responsibilities include conducting workshops, developing educational materials, and providing one-on-one consultations with farmers.

Extension educators are trained not only in technical agricultural sciences but also in adult learning theory, participatory facilitation, and systems-based problem solving (Caillouet, 2022; Cristóvão et al., 2012). Professional development programs increasingly emphasize intercultural competence and inclusive engagement strategies to serve diverse agricultural communities (Diaz et al., 2022; Shehu, 2018).

Strengths and challenges of the US extension system

The US extension system's strengths lie in its robust institutional framework, advanced technological integration, and emphasis on professional development. However, challenges persist, including funding disparities across states, the digital divide in rural areas, and the need to engage younger generations in agriculture. Addressing these challenges will require sustained investment, innovative outreach strategies, and stronger collaborations between public and private entities (APLU, 2021; Ding, 2015). The US agricultural extension system serves as a model for leveraging research, education, and technology to address the needs of rural and agricultural communities. Its adaptability and focus on continuous improvement make it a valuable reference for other countries seeking to enhance their extension services.

Evolution of Rwanda's Agricultural Extension

Rwanda's extension system has gone through several transformations. There were no extension services before colonization, instead, people exchanged goods and information in their communities (Harrison, 2016; Kiptot et al., 2016). During colonization, the colonizers introduced extension services mainly by focusing on cash crops such as coffee, tea, and pyrethrum, but the system was exploitative (Kayitesi, 2019; Mizero et al., 2018). In the same period, to fight against the famine, the colonizers also introduced food crops such as cassava, and sweet potato (Mizero et al., 2018). After independence, Rwanda adopted a highly centralized extension system that relied heavily on top-down knowledge dissemination from government agronomists to farmers (Kiptot et al., 2016; Ministry of Agriculture and Animal Resources [MINAGRI], 2023). Grassroots extension officers worked under the oversight of district and sector agronomists to deliver services directly to farmers. However, this system was often hindered by limited resources, a lack of farmer involvement, and a failure to address the diverse needs of local communities (MINAGRI, 2023).

In 1982, Rwanda officially adopted a centralized extension system. The purpose of this extension service was to enhance collaboration between Rwandan local authorities and farmers. In 1986, training and farmer visits started. However, the new system was introduced to replace the old one but the liberation war hindered its implementation (Kiptot et al., 2016; MINAGRI, 2023). After 1994, the Farmer Field School (FFS) extension service systems were introduced. This participatory learning method engaged farmers in agricultural training and equipped them with the skills necessary to adopt best farming practices and improve yields (Kiptot et al., 2016; MINAGRI, 2023). The FFS was complemented by the Twigire Muhinzi extension model, a decentralized farmer-to-farmer system introduced in 2014 to enhance knowledge transfer and technology adoption (MINAGRI, 2023; Silvestri et al., 2019). Twigire Muhinzi is a homegrown model that combines the FFS approach with farmer promoters, to leverage their local expertise and foster social cohesion while empowering farming communities which enables farmers to lead local knowledge-

sharing initiatives, Twigire Muhinzi promotes sustainability, community ownership, and long-term agricultural development (MINAGRI, 2023; Mutabaruka et al., 2022).

Use of ICT in agricultural extension activities

Rwanda has embraced ICT as a catalyst for agricultural innovation and extension. Rwanda has substantially increased the number of broadcast media establishments in the last two decades due to media reforms implemented between 2002 and 2022. During this time frame, the number of radio stations expanded from 1 to 38, while the quantity of television licenses rose from 1 to 17. From 2002 to 2007, print media increased from 15 to 61, but a significant decrease to 9 was noticed after 2007. Between 2002 and 2022, the widespread adoption of ICT led to a substantial growth in online or digital media, rising from 1 to 17 (RGB, 2022). For instance, Rwanda's mobile phone adoption rate is 85%, while the Internet adoption rate is 62%. Approximately 66% of households have access to electricity, 81% own a radio, 12% own a TV, and 4% own a computer (RGB, 2022). The literacy rate is 77%, with a significant portion of the population being youth under 35 (Rwanda Utility Regulatory Authority [RURA], 2022). The use of digital tools has shown significant capacity in distributing information to farmers and enhancing economic prospects (Kabirigi et al., 2022; Musafiri, 2016). According to research by Musafiri (2016), over 45% of households in Rwanda use mobile technology. Among these mobile users, 38% have achieved higher agricultural output than non-users, resulting in an average income increase of 26%.

The digital platform, e-soko is a technology platform used in several African countries that integrates mobile and online tools to improve access to agricultural extension services and market information. By reducing the cost of accessing market data, it provides farmers with real-time weather updates and extension advice, helping them make informed decisions (Ayim et al., 2022). In Rwanda, e-Soko has been implemented through a partnership between the MINAGRI (2023) and the Ministry of Information and Communication Technology and Innovation. The platform is managed by MINAGRI (2023), while local agents are responsible for collecting real-time market price information from various markets across the country. e-Soko serves as a vital tool for farmers by enabling them to access accurate price information, allowing them to sell their produce where they can earn the highest return. This system has contributed to greater market transparency and helped stabilize commodity prices (FAO, 2020). In addition, mobile applications and animated videos, such as those developed by scientific animations without borders (SAWBO), translate scientific agricultural information into local languages and make this information accessible even to individuals with lower literacy rates in remote areas (Bello-Bravo et al., 2018; Maredia et al., 2018) These innovations enhance knowledge sharing on best practices, disease management, and post-harvest handling, bridging the gap between farmers and extension services (Yongabo, 2022).

Strengths and challenges

Rwanda's agricultural extension system benefits from its integration of cultural practices, use of ICT, and focus on participatory approaches. Smallholder farmers, who form the backbone of Rwanda's agriculture sector, are the primary beneficiaries of its extension services. Programs like Twigire Muhinzi empower farmer promoters to act as intermediaries, disseminating knowledge and facilitating peer learning within their communities (Food and Agriculture Organization & International Food Policy Research Institute [FAO & IFPRI], 2021). Community-based approaches ensure that extension services are tailored to local needs, fostering higher adoption rates of agricultural innovations. However, challenges persist, including infrastructure limitations in remote areas, variable quality of training for extension agents, and the high cost of scaling digital solutions (Musafiri, 2016; Neza et al., 2021). Furthermore, since 1994, various organizations, including NGOs, have become involved in extension services. However, each organization pursues its objectives, leading to multiple organizations providing different extension services to farmers, creating confusion arising from diverse and conflicting information (Kiptot et al., 2016).

Nigerian Agricultural Extension System

Agricultural extension services in Nigeria have evolved significantly, reflecting the country's socio-economic changes and global agricultural trends. In pre-colonial times, informal knowledge transfer systems dominated, with indigenous practices guiding farming. The colonial era marked the establishment of formal extension systems, starting with the moor plantation in Ibadan in 1910, aimed at boosting agricultural productivity for colonial economic needs (Adedipe et al., 1995; Aina et al., 2019; Ajayi & Adeoti, 2019). Post-independence in 1960 saw the expansion of extension services through regional ministries of agriculture, focusing on cash crop promotion. However, the oil boom in the 1970s led to a decline in agricultural investments. To revive the sector, the green revolution in the 1980s introduced high-yield crops, fertilizers, and mechanization alongside expanded extension efforts (Adedipe et al., 1995; Akinyemi, 1987; Ani et al., 2015). World Bank-funded agricultural development projects (ADPs) in the 1980s and 1990s introduced the training and visit (T&V) system, improving knowledge dissemination but facing challenges like funding shortfalls (Aina et al., 2019; Axinn, 1988). In the 2000s, decentralization and PPPs emerged, exemplified by the GESS, which used e-wallets to deliver subsidized inputs (Adesina, 2012; Akinbode, 1982). ICT integration in recent years has transformed extension services, enabling farmers to access real-time information and markets through platforms like FarmCrowdy (Arokoyo, 2006; Oladele, 2011). Despite challenges such as limited funding and infrastructure, Nigeria's agricultural extension system continues to adapt, ensuring its relevance in supporting farmers and fostering agricultural development.

Challenges of diversity and regional differences

Agricultural extension in Nigeria operates within a highly diverse socio-economic and cultural landscape. As the most populous country in Africa, Nigeria is characterized by significant variations in agrarian practices, climatic conditions, and regional needs (Adisa, 2011; Camillone et al., 2020; Lai-Solarin et al., 2024; Shehu, 2018). These differences pose substantial challenges to the effectiveness of its agricultural extension system. Nigeria's agro-ecological zones range from the arid Sahel in the north to the humid rainforest in the south. This diversity necessitates region-specific agricultural extension approaches (Enete & Amusa, 2010;

Gowland-Mwangi, 2012). While the northern regions primarily rely on cereal and legume cultivation, the southern areas emphasize root and tuber crops and cash crops like cocoa (Aker, 2011; Arowosegbe et al., 2024; Enete & Amusa, 2010;).

The stark differences in these practices require extension agents to be well-versed in localized agricultural technologies and methods, which can stretch resources and training capacities. Nigeria is home to over 250 ethnic groups and languages, adding complexity to communication and outreach efforts. Effective agricultural extension services depend on the ability of agents to bridge language barriers and navigate cultural norms. In many rural communities, local languages are the primary medium of communication, and agricultural terminologies in English or Hausa (a lingua franca in the north) may not translate directly into other languages spoken in the south or central regions (Lai-Solarin et al., 2024; Shehu, 2018). This can hinder the dissemination of critical farming innovations (Adetayo & Eunice, 2013; Shehu, 2018)

Regional disparities in infrastructure and resource availability further exacerbate the challenges. Northern Nigeria, for example, suffers from lower levels of road connectivity and access to agricultural markets compared to the south. This uneven development affects the delivery of extension services and the adoption of new technologies, leaving some regions more marginalized than others (Arowosegbe et al., 2024; Oladele, 2011). Climate conditions intensifies regional differences, with northern Nigeria experiencing desertification and reduced rainfall, while southern regions grapple with flooding and soil erosion (Ikuemonisan, 2024; Koyenikan, 2008; Lai-Solarin et al., 2024; Shehu, 2018). These ecological stresses demand context-specific extension strategies, which are often underdeveloped due to lacking targeted training and funding (FAO, 2017).

Use of ICT in Extension Activities

The integration of ICT into Nigeria's agricultural extension system has revolutionized the dissemination of information and services to farmers. ICT tools such as mobile phones, radio, television, and Internet platforms are widely used to bridge the knowledge gap between extension agents and farmers, fostering improved productivity and agricultural outcomes (Ezeh Ann, 2013; Idrisa et al., 2013). Mobile technology is particularly transformative, with over 90% of Nigerians owning a mobile phone. Farmers leverage mobile platforms to access timely information on weather, market prices, pest, and disease management, and input availability (Aker & Fafchamps, 2015; Sennuga, 2019). The E-Wallet system introduced under the GESS exemplifies ICT's impact, enabling farmers to receive subsidized inputs like fertilizers and seeds directly via mobile phones (Adesina, 2012; Tanko et al., 2013). Mass communication tools such as radio and television remain effective, especially in rural areas. Agricultural programs in local languages educate farmers on best practices and innovations. Internet-based platforms and social media are increasingly popular among younger farmers, promoting interactive communication and peer learning (Asenso-Okyere & Mekonnen, 2012).

Emerging Themes Across the Three Countries

Capacity building in agricultural extension

Capacity building is a core component of agricultural extension systems, ensuring farmers and extension agents acquire the knowledge, skills, and resources necessary for sustainable agricultural practices (Anderson & Feder, 2007). In the United States, capacity building is embedded in the CES, which operates through land-grant universities, delivering research-based agricultural education and continuous professional training for extension agents (APLU, 2012; Ding, 2015). Extension professionals undergo structured training programs, including earning university degrees, workshops, certifications, and hands-on demonstrations that bridge research and practice. However, in Rwanda, capacity-building efforts focus on community-led agricultural knowledge exchange through the Twigire Muhinzi model. This approach emphasizes farmer-to-farmer training, where local farmer promoters trained by government and NGOs facilitate participatory learning through FFS (MINAGRI, 2023; Silvestri et al., 2019). Rwanda's model is deeply embedded in cultural frameworks such as Umuganda, where collective community work strengthens knowledge sharing and the adoption of improved agricultural practices (Flinkenflogel et al., 2015). In Nigeria, capacity-building efforts aim to integrate public and private sector expertise. Programs such as the GESS enhance farmers' access to training on ICT-based extension tools and climate-smart practices (Adefalu et al., 2023; Adesina, 2012). However, regional disparities in training and funding constraints limit the program's effectiveness, particularly in rural northern regions where access to extension services remains low (Ajayi & Adeoti, 2019).

Despite their structural differences, all three countries recognize that extension systems are only as effective as the capacity of their educators and farmers. Strengthening institutional support, integrating participatory methods, and fostering international collaborations could enhance capacity-building efforts globally (Benson & Jiggins, 2017; Cristóvão et al., 2012).

Technology integration in agricultural extension

The integration of technology in agricultural extension services enhances knowledge dissemination, increases efficiency, and improves farmers' access to real-time agricultural information (Aker, 2011). In the United States, digital extension platforms, mobile apps, and remote sensing technologies play a crucial role in precision agriculture. Extension agents use GIS and digital advisory tools to provide farmers with data-driven insights on soil health, pest control, and irrigation management (APLU, 2021; Ding, 2015). The widespread use of digital platforms enables farmers to participate in online learning and access up-to-date agricultural research without geographic limitations. On the other hand, in Rwanda, technology integration focuses on mobile-based advisory services tailored to smallholder farmers. Platforms such as e-Soko provide real-time market and weather information, improving farmers' decision-making processes (Malabo Montpellier Panel, 2019; Musafiri, 2016). Moreover, animated videos from SAWBO translate complex agricultural information into local languages, making knowledge accessible even to farmers with low literacy levels (Bello-Bravo et al., 2018; Maredia et al., 2018).

Similarly, Nigeria has leveraged ICT-driven agricultural extension, particularly through mobile phone platforms, radio programs, and the e-wallet system under GESS. This system allows farmers to receive agricultural inputs such as fertilizers and seeds through mobile transactions, reducing corruption in input distribution (Adesina, 2012; Tanko et al., 2013). However, digital literacy remains a significant barrier, particularly in rural areas with limited access to Internet services (Aker & Fafchamps, 2015; Owolabi & Yekinni, 2022; Sennuga, 2019). Across these three contexts, technology integration has transformed agricultural extension from traditional, face-to-face interactions to hybrid models combining digital tools with in-person advisory services. Future efforts should focus on bridging the digital divide, enhancing ICT literacy, and promoting cross-border collaboration on digital agricultural innovations (Jere & Maharaj, 2017; Owolabi & Yekinni, 2022).

Beyond digital literacy and Internet access, additional structural barriers affect technology adoption across the three contexts. Infrastructure reliability, including inconsistent electricity supply in rural Nigeria and parts of Rwanda, limits sustained digital engagement (FAO, 2017). Device affordability remains a constraint for smallholder farmers, particularly where smartphone penetration lags behind basic mobile phone ownership. Furthermore, data costs and network instability reduce consistent access to advisory platforms. These infrastructural and economic constraints highlight that digital extension requires not only technological tools but enabling ecosystems that ensure equitable access.

Educators' preparation in agricultural extension

The effectiveness of agricultural extension services largely depends on the quality of extension educators. In the United States, extension agents undergo formal training from universities and participate in structured professional development systems that integrate both technical and pedagogical skills. These systems combine formal training approaches such as workshops, certification programs, and guided instruction with informal learning mechanisms, including mentoring, peer collaboration, and on-the-job experience, enabling continuous competency development throughout an educator's career (Cummings et al., 2015).

Professional development programs provide ongoing training in adult education methodologies, agricultural research applications, and digital extension tools, making extension educators more adaptable to emerging challenges (Benson & Jiggins, 2017). In Rwanda, educator preparation is embedded within the community-based Twigire Muhinzi model, a decentralized extension system that builds on the FFS approach, where trained farmer promoters serve as localized extension agents facilitating peer-to-peer learning and knowledge dissemination within their communities.

While this approach fosters trust and enhances participatory learning, challenges arise from the limited formal training opportunities for farmer promoters, which can hinder the quality of knowledge transfer (MINAGRI, 2023; Silvestri et al., 2019). Efforts to standardize training curricula and offer refresher courses could enhance the effectiveness of Rwanda's extension educators.

In Nigeria, educator preparation varies widely across regions, with extension officers trained through PPPs and university-affiliated programs. While initiatives such as the ADPs and the T&V system have improved extension education, inconsistencies in funding and regional disparities limit nationwide access to well-trained educators (Ajayi & Adeoti, 2019; Omoregie & Koyenikan, 2020). Additionally, gender disparities in educator recruitment remain a barrier, as female farmers often have less access to female extension officers (Arowosegbe et al., 2024).

Despite these challenges, all three countries recognize the importance of equipping extension educators with both technical and interpersonal skills. Strengthening educator training through standardized curricula, digital learning resources, and collaborative exchange programs could significantly enhance agricultural extension services worldwide (Arowosegbe et al., 2024).

CONCLUSION

Agricultural extension services play a pivotal role in enhancing farmer education, improving agricultural productivity, and promoting sustainable farming practices. This comparative analysis of the United States, Rwanda, and Nigeria highlights three fundamental themes that shape the effectiveness of extension models: capacity building, technology integration, and educator preparation. Despite differences in historical evolution and structural design, all three countries share a common goal of ensuring farmer empowerment, technology-driven innovation, and sustainable agricultural development. The US CES demonstrates a well-established framework that integrates land-grant universities, advanced digital tools, and professional development for extension educators. Rwanda's decentralized Twigire Muhinzi model leverages community-based participation, farmer-led training, and mobile-based advisory services to promote knowledge transfer. Nigeria's extension approach, characterized by PPPs and ICT-driven interventions, aims to bridge the gap between research institutions and rural farmers, despite regional disparities and infrastructure challenges.

This study contributes to the agricultural extension literature by providing a comparative, cross-country analysis grounded in three key dimensions: capacity building, technology integration, and educational preparation across both Global North and Global South contexts. While existing studies often focus on single-country extension systems or isolated themes, this study integrates these dimensions to show how extension effectiveness emerges from the interaction between institutional structures, community-based approaches, and technological systems. Specifically, the analysis demonstrates

(1) how formal, university-led systems (US) and decentralized, farmer-led models (Rwanda) can complement one another,

(2) how ICT-driven approaches (Nigeria and Rwanda) are shaped not only by access but also by infrastructure, affordability, and local content relevance, and

(3) how continuous professional development of extension educators remains a critical but differently structured component across contexts.

By synthesizing these insights, the study offers a more holistic and transferable understanding of how agricultural extension systems can be designed to be context-sensitive, adaptive, and inclusive.

A key insight from this study is that no single extension model is universally superior; rather, successful agricultural extension systems are context-specific, leveraging cultural, technological, and institutional strengths to address farmers' unique needs. Moving forward, enhancing cross-country collaboration, improving digital access, and strengthening educator training programs will be essential in fostering resilient and adaptive agricultural extension services

Recommendations

Agricultural extension remains a cornerstone of global food security, rural development, and sustainable agriculture. The experiences of the United States, Rwanda, and Nigeria offer valuable lessons on how different extension models can adapt to local needs, leverage technology, and prioritize farmer empowerment. Through the integration of best practices from each system, countries can create inclusive, participatory, and technology-driven extension services that equip farmers with the knowledge and skills necessary for agricultural resilience and economic growth. To enhance agricultural extension systems in the United States, Rwanda, and Nigeria, five recommendations are proposed:

1. Expanding farmer-to-farmer learning, community extension programs, and FFS can enhance localized knowledge transfer and participation.
2. Training both farmers and extension agents in using digital platforms, mobile advisory tools, and online learning resources will maximize the potential of technology-driven extension models.
3. Establishing structured training curricula and continuous professional development will ensure extension educators remain up to date with agricultural innovations and adult learning techniques.
4. Strengthening private sector involvement and government collaborations will enhance funding, scalability, and access to technology-driven extension services.
5. Creating cohesive agricultural extension policies and ensuring collaboration between governments, NGOs, and research institutions will lead to more structured and impactful extension programs.

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