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Not a Technology Gap but a Fit Gap in African Smallholder Livestock Systems

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Abstract

Despite significant investments in agricultural technologies and innovation systems, the uptake of emerging technologies in smallholder livestock systems in sub-Saharan Africa (SSA) remains low. Traditional agricultural transformation strategies have been mostly technology-oriented and one-size-fits-all approaches that often do not reflect the socioeconomic, institutional, sociocultural, digital, and environmental realities of smallholder livestock farmers' lives. Consequently, many innovations, such as digital advisory platforms, artificial insemination technologies, commercial feed systems, veterinary pharmaceuticals, vaccines, precision livestock tools, and other input-intensive interventions, are out of reach, too expensive, ill-suited, or not sufficiently responsive to local production conditions and farmer priorities. In this study, we propose that the key barrier to the uptake of livestock innovation in SSA is not the absence of technologies, but rather a systemic "Fit Gap" between the design of new agricultural innovations and the realities of smallholder livestock systems. The Fit Gap is a multidimensional mismatch of economic, institutional, digital, sociocultural, and environmental factors that constrain the uptake, sustainability, and scale-up of livestock technologies in resource-constrained farming systems in developing countries. Through a systematic narrative literature review of Scopus-indexed literature between 2020 and 2026 and evidence from Zimbabwe, Kenya, Nigeria, Ethiopia, Ghana, and Zambia, this study identified four interconnected dimensions of misalignment: (1) economic barriers related to affordability and financial risks; (2) institutional and digital barriers related to weak extension systems, inadequate infrastructure, and unequal digital access; (3) sociocultural exclusion related to limited integration of gender perspectives and Indigenous Knowledge Systems (IKS); and (4) environmental incompatibilities related to climate variability, droughts, feed shortages, and ecological stressors. This study proposes a Fit-Oriented Agricultural Innovation Framework based on participatory co-design, affordability, climate resilience, gender inclusivity, contextual adaptation, and adaptive institutional support. The framework emphasizes the need to integrate Indigenous Knowledge Systems, climate-smart livestock practices, and inclusive digital innovations to improve the relevance, accessibility, and sustainability of livestock technologies. The study concludes that sustainable livestock transformation in SSA requires a shift from technocentric models of modernization to context-responsive, socially embedded, and resilience-oriented innovation systems that position smallholder farmers as active co-creators of innovation.

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1. Introduction

Livelihoods, food security, and economic development in sub-Saharan Africa (SSA) are underpinned by agriculture, and smallholder livestock systems are a key contributor to household income, nutrition, asset accumulation, and resilience to climatic and economic shocks (FAO, 2023). Livestock production provides meat, milk, eggs, manure, draught power, and socio-cultural value and contributes to the livelihood diversification of rural households (Rose *et al*., 2021). Governments, development agencies, research institutions, and private sector actors have invested heavily in digital, genetic, veterinary, and climate-smart innovations for livestock over the last two decades to improve the productivity, sustainability, market engagement, and resilience of smallholder farming systems (Finger *et al*., 2023).Even with such investments, livestock transformation in SSA is limited and patchy. The adoption of technology by smallholder livestock producers remains low, fragmented, and inconsistent across production systems. Many innovations that are successful in experimental or commercial situations are not adopted in the long run in resource-constrained rural settings (Klerkx, 2023). Structural barriers, such as weak extension systems, poor infrastructure, limited access to markets, low levels of digital literacy, limited veterinary services, and limited access to finance, have been attributed to low adoption. However, these are part of the story and do not fully explain why many technologies are still not accessible, affordable, or environmentally appropriate or well-aligned with local production realities and farmer priorities (Finger *et al*., 2023).

The main challenge for the adoption of livestock innovations in SSA is not the lack of technologies but a chronic contextual mismatch between the design of emerging agricultural innovations and the realities of smallholder livestock systems. This misfit is referred to as the “Fit Gap” in this study, a term that describes the multidimensional disconnect of livestock technologies to the socioeconomic, institutional, sociocultural, digital, and environmental conditions in which smallholder farmers operate. Much agricultural innovation originates in formal systems, which assume stable markets, reliable infrastructure, adequate purchasing power, and predictable production conditions. However, smallholder livestock systems in SSA are often characterized by climatic uncertainty, weak institutional support, informal markets, resource limitations, and a heavy reliance on Indigenous Knowledge Systems (IKS) and local coping strategies. Thus, farmers are more inclined towards cheap, flexible, robust, and risk-reducing technologies than productivity-oriented ones (Klerkx *et al*., 2020; Kok *et al*., 2023).

This study thus urges a move away from (technology-driven) top-down approaches to the modernization of livestock systems towards participatory, context-specific, and resilience-oriented livestock innovation systems. This study explores the influence of fit-gap on technology adoption in smallholder livestock systems through a literature review (2020-2026) and evidence from Zimbabwe, Kenya, Nigeria, Ethiopia, Ghana, and Zambia. It also promotes a Fit-Oriented Agricultural Innovation Framework of participatory co-design, gender sensitivity, climate resilience, Indigenous Knowledge, inclusive digital innovation, and flexible institutional support. This study contributes to the scholarship on agricultural innovation and policy discourse by advancing ways of repackaging livestock technologies to better fit the realities of smallholder livestock farmers in SSA.

2. Literature Review

2.1. Digital Agriculture and Adoption Constraints in Smallholder Livestock Systems

Digital agriculture is increasingly hailed as a major avenue for transforming smallholder livestock systems in sub-Saharan Africa (SSA) via enhanced productivity, health management, market access, and climate resilience. Technologies such as mobile-based advisory services, precision livestock tools, remote sensing, electronic marketing platforms, and data-driven decision support systems can be leveraged to reduce information gaps, improve the delivery of veterinary and extension services, and support livestock management decisions. However, the uptake of digital livestock technologies is patchy and limited in many parts of SSA (Nxumalo, 2025).

There are several structural and socioeconomic barriers to the uptake of digital innovations in smallholder livestock systems. Limited access to affordable digital devices, poor mobile network coverage, unreliable electricity, and poor internet connectivity limit farmers’ access to tele-veterinary services, digital extension platforms, and climate information systems. A further barrier to the successful integration of digital technologies in livestock management practices is the poor digital literacy of older and resource-poor farmers. Many rural households also do not have the means to purchase expensive smartphones, mobile data, and digital tools, and limited access to credit restricts investment in such technologies. Digital exclusion is often compounded by gender inequalities, as women farmers usually have limited access to education, finance, land ownership, and mobile technology (Choruma *et al*., 2024).

The digital divide remains with inequalities in rural livestock systems, where the benefits of digital technology are often skewed in favor of better-off and commercially oriented farmers. Likewise, many digital livestock interventions use standardized models that do not account for Indigenous knowledge, local languages, literacy levels, and sociocultural realities. Technologies can therefore be considered irrelevant, culturally inappropriate, or difficult to use. Furthermore, many interventions are based on top-down approaches that favor technical sophistication over farmer participation and context adaptation. These limitations highlight the need for more participatory and context-responsive digital innovation systems that are more inclusive and address affordability, gender inclusivity, integration of local knowledge, digital capacity building, and user-centered design in smallholder livestock systems across SSA.

2.2. Economic Barriers to Input Technologies in Smallholder Livestock Systems

Economic constraints to the adoption of input-intensive livestock technologies in sub-Saharan Africa (SSA), such as improved feeds, veterinary pharmaceuticals, artificial insemination, vaccines, and commercial breeding stock, persist. Although promoted for improved productivity, animal health, and food security, the uptake of these technologies by smallholder livestock farmers is low because of high input costs, limited purchasing power, and uncertainty of economic returns. Most smallholder farmers are low-income, asset-poor, and vulnerable to climate and market shocks. This means that many farmers do not invest in costly technologies and follow low-input traditional production systems that are considered less risky under uncertainty (Forero, 2025).

Poor institutional support and weak rural financial systems exacerbate these challenges in many SSA countries. The limited infrastructure and low levels of financial inclusion mean that access to affordable credit and livestock insurance schemes is limited and often underdeveloped or nonexistent. In addition, investments in productivity-enhancing technologies are disincentivized by unstable value chains, price volatility, and weak market integration. This implies that many smallholder livestock systems are trapped in a cycle of low investment, low productivity, and persistent rural poverty (African Union, 2023).

There is evidence that the existence of technology does not necessarily lead to its adoption. Farmer education, training opportunities, social learning networks, and access to extension services strongly influence uptake (Choruma *et al*., 2024; Nxumalo, 2025). The findings demand integrated interventions combining technology dissemination with financial inclusion, market development, farmer training, and institutional support for improved uptake and sustainability of livestock innovations in SSA.

2.3. Climate Change and Environmental Stressors in Smallholder Livestock Systems

Smallholder livestock systems in sub-Saharan Africa (SSA) are increasingly threatened by climate change and environmental variability, jeopardizing livestock productivity, household livelihoods, and food security. Unpredictable rainfall, prolonged droughts, late onset of rains, and recurrent dry spells interfere with grazing systems, decrease the availability of forage, and limit access to water for livestock. Such climatic stresses have negative effects on animal nutrition, reproductive performance, growth rates, and productivity, particularly in rain-fed and extensive smallholder systems. Smallholder farmers are especially vulnerable, with limited financial resources, infrastructure, and access to climate adaptation technologies and support services (IPCC 2022; FAO 2023).

Climate change is also increasing the occurrence and distribution of pests, parasites, and livestock diseases throughout SSA. Changes in temperature and ecological conditions create favorable conditions for disease vectors, such as ticks, which leads to an increase in the incidence of tick-borne diseases and other health problems in livestock. Increased feed intake, fertility, milk production, and animal survival are limited by heat stress and water deficiency, especially in the arid and semi-arid zones of the world. These environmental pressures usually require sophisticated management practices, veterinary services, and adaptive husbandry systems, which many smallholder farmers cannot afford or access (FAO, 2023; World Bank 2021).

In addition to the direct production challenges, climate change results in more uncertainties and risks in livestock production systems. This reduces the efficiency of technologies that increase productivity under stable production conditions, such as improved feeding systems, exotic breeds, and intensive management practices. Resource-poor farmers face economically risky investments in improved livestock technologies because of feed shortages, water stress, and disease outbreaks.

Further limiting adaptive capacity are restricted access to climate information, early warning systems, insurance, veterinary support, and climate-smart technologies. This has resulted in many farmers being trapped in low-input, low-output systems, leading to low productivity and chronic poverty. These challenges can be addressed through context-specific and climate-resilient livestock innovations, such as adapted indigenous breeds, improved rangeland management, climate-smart husbandry practices, and integrated institutional and policy support systems to promote resilience and sustainability in rural livestock communities (IPCC 2022; World Bank 2021).

2.4. Institutional and Systemic Gaps in Smallholder Livestock Systems

Institutional and systemic weaknesses largely hamper the uptake of innovation and the sustainable transformation of smallholder livestock systems in sub-Saharan Africa (SSA). In many countries, livestock innovation systems are largely top-down and supply driven, where technologies are developed by researchers, governments, and development agencies, with limited involvement of smallholder farmers. Technically, these innovations may be sound, but they often do not reflect local socio-economic realities, resource limitations, production objectives, and cultural practices. This has led to many livestock technologies being unaffordable, unadaptable, and lacking contextual relevance, leading to low adoption rates across SSA (Choruma *et al*., 2024; Forero, 2025).

The challenges are further compounded by disjointed institutional systems and poor coordination among the stakeholders. Weak links between research institutions, extension services, universities, policymakers, financial institutions, private sector actors, and farmer organizations lead to inefficiency in technology development and dissemination. Livestock extension systems are often under-resourced and understaffed, limiting farmers' access to technical support, veterinary services, and training. Investment constraints include weak rural infrastructure, poor market systems, limited digital connectivity, poor veterinary services, and limited access to affordable credit and insurance (African Union, 2023; World Bank, 2021).

Evidence suggests that participatory and multistakeholder approaches can enhance technology adoption and sustainability in smallholder livestock systems. More relevant, acceptable, and owned have been inclusive innovation models that integrate farmers, researchers, extension workers, policymakers, and private sector actors in the co-design and adaptation of technologies. Approaches such as farmer field schools, innovation platforms, community-based breeding programs, and public-private partnerships are used to improve knowledge exchange and contextual adaptation. Thus, enhancing institutional coordination, extension systems, policy support, and inclusive innovation processes is crucial for improving livestock productivity, climate resilience, and sustainable rural livelihoods in SSA (Metcalfe, 2024).

3. Methodology

This study adopted a systematic narrative review approach to assess the uptake of agricultural technologies and innovations in smallholder livestock systems in sub-Saharan Africa (SSA). This approach allowed the synthesis of multidisciplinary evidence from agricultural innovation, livestock systems, climate resilience, digital agriculture, and policy studies to investigate the socioeconomic, institutional, environmental, and sociocultural drivers of technology adoption. The review examined literature from 2020-2026 to include recent developments in digital agriculture, climate-smart livestock systems, participatory innovation, Indigenous Knowledge Systems (IKS) and gender-responsive approaches in sub-Saharan Africa (SSA).

Literature was searched through Scopus, Web of Science, ScienceDirect, Google Scholar, SpringerLink, Wiley and institutional repositories of FAO, World Bank, African Union, ILRI and IPCC. Key search terms were "smallholder livestock systems", "digital agriculture", "livestock innovation", "technology adoption", "climate-smart livestock systems", "Fit Gap", and "Sub-Saharan Africa". Comparative analyses were done through additional searches in Zimbabwe, Kenya, Nigeria, Ethiopia, Ghana and Zambia. The review included peer-reviewed articles, policy reports, technical reports, and institutional publications relevant to livestock technologies, climate adaptation, and innovation systems for SSA countries. Methods were selected on the basis of relevance to the topic, methodological quality and adherence to the aims of the study.

The findings were classified into four major themes using thematic content analysis: (1) economic and affordability constraints; (2) institutional and digital innovation gaps; (3) sociocultural and gender dimensions; and (4) environmental and climate-related stressors. The impact of these factors on technology adoption across the three countries' smallholder livestock systems was explored using a cross-country comparative analysis. The study then developed a Fit-Oriented Agricultural Innovation Framework that incorporates evidence from participatory innovation systems, climate-smart agriculture, Indigenous Knowledge Systems, and inclusive digital approaches. Despite the reliance on secondary data, the methodological rigor of this study was enhanced by triangulation across multiple peer-reviewed and institutional sources of data. Despite challenges such as publication bias and differing availability of country-specific data, this study provides useful conceptual and empirical evidence on the multidimensional constraints to livestock technology adoption in SSA.

4. Results and Discussion

4.1. The Design–Reality Gap in Smallholder Livestock Systems

The persistent gap between design and reality is one of the most important challenges in implementing emerging agricultural technologies in smallholder livestock systems in sub-Saharan Africa (SSA). Many innovations are based on technology-based approaches that emphasize capital intensity, advanced infrastructure, standard production systems, and specialized technical expertise. These technologies are meant to increase productivity and commercialization, but they often do not fit into the socio-economic, institutional, and environmental realities of smallholder livestock farmers in developing countries. Most smallholder producers operate in resource-constrained environments, which are characterized by low income, weak infrastructure, limited access to finance, poor market integration, and high exposure to climatic risks. Moreover, indigenous knowledge systems, traditional management practices, and locally adapted coping strategies of livestock production systems are highly dependent on different agroecological environments (Choruma *et al*., 2024; Klerkx *et al*., 2022).

This mismatch restricts the uptake and sustainability of agricultural innovations in smallholder farming systems. Technologies that work well in commercial or experimental settings may be too expensive or impractical for resource-poor farmers to adopt them. The high costs of improved housing, mechanized feeding systems, precision livestock technologies, advanced breeding programs, and digital tools often discourage adoption rates, as farmers consider them financially risky or inconsistent with local production priorities (Ogutu *et al*., 2023; Forero, 2025). In addition, infrastructure-dependent technologies are difficult to implement in rural areas, where bad roads, no electricity, weak Internet, little water infrastructure, and poor veterinary services can all reduce their effectiveness. This can render digital livestock advisory systems, automated feeding technologies, and climate monitoring tools unavailable and/or unviable within remote communities (World Bank, 2021; FAO, 2023).

Knowledge-intensive technologies also require technical skills, formal education, and extension support, which are often lacking in smallholder communities. Many innovations have come from formal scientific systems that make poor use of Indigenous knowledge and local experiential learning. However, for breeding, feed management, disease control, climate adaptation, and risk management in many SSA livestock systems, Indigenous knowledge systems are still important. Such technologies can be culturally inappropriate or difficult to implement if farmers do not consider local realities (Klerkx *et al*., 2022; Rooyen *et al*., 2021). Bridging the design-reality gap requires innovative approaches that are more inclusive, participatory, and context-responsive, and that prioritize affordability, climate resilience, integration of local knowledge, gender sensitivity, and farmer participation. Bridging this gap is critical for improving technology adoption, building resilience, and enhancing the sustainability of smallholder livestock livelihoods in sub-Saharan Africa.

4.2. Digital Agriculture: Promise versus Reality in Smallholder Livestock Systems

There is growing discussion on digital agriculture as a pathway to improved productivity, efficiency, and resilience in smallholder livestock systems in sub-Saharan Africa (SSA). Technologies such as mobile-based advisory services, remote sensing, precision livestock tools, electronic marketing platforms, and data analytics can improve access to information, veterinary support, market participation, and climate-smart livestock management. These innovations help with decision-making regarding animal health, feeding, breeding, and climate adaptation while reducing transaction costs and improving market linkages in livestock value chains (Choruma *et al*., 2024; Klerkx *et al*., 2022; Aker & Fafchamps, 2022). However, major structural and socioeconomic barriers constrain the potential impact of digital agriculture.

Limited access to affordable digital devices, poor mobile network coverage, poor Internet connectivity, and unreliable electricity reduce farmers' ability to use digital advisory platforms, online marketing systems, and digital financial services (World Bank, 2021; FAO, 2023). Many digital technologies are not suitable for local contexts, often ignoring local languages, literacy levels, cultural norms, gender dynamics, and Indigenous knowledge systems. This suggests that some digital tools remain difficult to use or are irrelevant to the production realities of smallholder livestock farmers (Baumüller, 2022; Baumüller, 2021).

The limited digital literacy of women, elderly farmers, and marginalized populations in rural areas further constrains the use of digital innovations. Concerns regarding trust, data privacy, misinformation, and digital fraud also hamper adoption. Digital livestock technologies are thus more likely to be owned by wealthier, more educated, or peri-urban farmers who have better access to infrastructure and technical know-how (Choruma *et al*., 2024; Nxumalo, 2025).

Bridging this digital fit gap requires inclusive and context-responsive approaches that prioritize affordability, accessibility, digital literacy, and user-centered designs. Low-cost solutions, such as SMS-based advisory systems, voice-based platforms, offline applications, and community digital centers, may improve access for resource-constrained communities. Moreover, the involvement of farmers and the incorporation of indigenous knowledge into digital innovation processes can improve the relevance, acceptability, and sustainability of digital agriculture for smallholder livestock systems in SSA.

4.3. Socio-Cultural Misalignment in Smallholder Livestock Systems

Major sociocultural mismatches are responsible for the poor adoption of new agricultural technologies in smallholder livestock systems in sub-Saharan Africa (SSA). Many livestock technologies have been developed in external frameworks that do not adequately consider cultural values, indigenous knowledge, local institutions, and community decision-making processes that affect rural livestock production. Smallholder livestock systems are embedded in social and cultural structures, where livestock management is driven by economic aspects, traditional beliefs, social norms, and experiential knowledge (Klerkx *et al*., 2022; van Rooyen *et al*., 2021). Technologies developed without reference to these realities often encounter resistance, low acceptance, or unsustainable adoption rates.

In many communities in SSA, indigenous knowledge systems continue to be the basis of livestock management practices, including breeding, disease control, grazing management, feed utilization, and climate adaptation practices that have been developed over generations. However, many modern technologies are promoted as one-size-fits-all solutions, without considering local knowledge and innovation systems, which in turn reduces the perceived relevance and trust of the farmers. Farmer groups, community networks, and traditional leadership structures are important influencers of livestock management and technology adoption. Technologies introduced without the participation of local institutions are often viewed as externally imposed and socially disconnected from the community's priorities.

Gender dynamics are also the engines of sociocultural misalignment. Women play an important role in livestock production and marketing but often face barriers to land ownership, access to finance, extension services, training, and decision-making opportunities (Doss *et al*., 2020; Njuki *et al*., 2022). Technologies that do not account for these differences may inadvertently perpetuate inequalities. Additionally, farmers often prefer informal knowledge-sharing networks, peer learning, and community demonstrations over formal extension systems to assess new technologies (Choruma *et al*., 2024; Kiptot *et al*., 2021).

To address sociocultural misalignment, inclusive and participatory innovation approaches that incorporate Indigenous knowledge, local governance systems, gender responsiveness, and farmer-led learning processes are required. The co-development of technologies with local farmers and improved community engagement can build trust, ownership, contextual relevance, and sustainability of livestock innovations in smallholder systems across SSA.

4.4. Climate Change as a Risk Multiplier in Smallholder Livestock Systems

Smallholder livestock systems in sub-Saharan Africa (SSA) are particularly susceptible to climate change, which is a major risk multiplier that increases their vulnerability and production uncertainty. Frequent droughts, floods, heat waves, erratic rainfall, and prolonged dry spells disrupt traditional livestock systems and threaten rural life. These climatic stresses affect forage availability, water access, animal health, reproductive performance, and livestock productivity, especially in rain-fed and extensive grazing systems that are dominant in smallholder production in SSA (IPCC, 2022; FAO, 2023). As climate variability increases, farmers become less certain about the outcome of production, market conditions, and household food security, which affects their decisions regarding the adoption of technology and risk management strategies.

In such uncertain conditions, many farmers prioritize livelihood security and risk minimization over productivity. Technologies such as better exotic breeds, commercial feed systems, mechanized production, and other input-intensive interventions are often seen as financially risky because their performance depends on stable feed supplies, water availability, veterinary support, and predictable climatic conditions (Herrero *et al*., 2021; Forero, 2025). Technologies that are not tailored to local climatic realities may fail during droughts, feed shortages, or disease outbreaks, feeding farmers' skepticism towards innovations promoted from outside (Hammond *et al*., 2020; World Bank, 2021).

Climate-induced stressors also exacerbate existing production challenges, such as rangeland degradation, declining pasture quality, water scarcity, and the spread of pests and livestock diseases. Heat stress reduces growth, fertility, milk production, and survival. Closing this climate-fit gap means integrating climate resilience into livestock innovation systems by fostering climate-resilient breeds, drought-tolerant forage systems, climate-smart husbandry practices, and integrated crop–livestock systems. Wider access to climate information services, early warning systems, and climate risk financing mechanisms, such as livestock insurance, can also help improve farmers' adaptive capacity and confidence in adopting improved livestock technologies. Therefore, it is imperative to incorporate climate resilience into agricultural innovation systems to improve the sustainability and scalability of livestock technologies in smallholder systems in SSA.

4.5. Gender and Indigenous Knowledge Systems in Bridging the Fit Gap in Smallholder Livestock Systems

4.5.1. Gendered Dimensions of the Fit Gap in Smallholder Livestock Systems

Gender relations critically shape access to agricultural technologies, resources, information systems, and decision-making in smallholder livestock systems in sub-Saharan Africa (SSA). Women are major contributors to livestock production, particularly in the management of poultry, goats, sheep, and other small ruminants, and are central to animal feeding, health care, processing, and marketing. Despite their contributions, female livestock farmers face structural inequalities that limit their access to land, livestock assets, financial services, extension support, training, digital technologies, and decision-making (Doss *et al*., 2020; Njuki *et al*., 2022). These inequalities contribute to a gendered fit gap, where innovations are technically available but inaccessible to many female livestock producers.

Many technologies assume equal access to resources, information, mobility, and support without considering the gender-differentiated constraints affecting technology adoption in smallholder systems. In many communities, women have little control over assets, limited financial access, and limited involvement in decision-making. Cultural norms and social responsibilities further restrict women's mobility, reducing their ability to attend training, interact with extension personnel, and participate in innovation platforms and organizations (Njuki *et al*., 2022). Therefore, women often miss opportunities to access and benefit from improved technology and services.

Gender inequality can be observed in digital agriculture projects that serve smallholder farmers. While digital technologies are intended to increase productivity, climate adaptation, and market integration, many do not consider the gender gaps in mobile ownership, Internet access, literacy, and digital skills. Women farmers often have lower access to devices, connectivity, financial resources, and technical training, limiting their participation in digital ecosystems (Klerkx *et al*., 2022). If these barriers are not overcome, digital interventions may entrench rather than reduce inequalities, thus hindering inclusive transformation and resilience.

Bridging the gendered fit gap requires gender-responsive and inclusive innovative approaches. This includes strengthening women-targeted extension services, improving access to land, credit, assets, and digital technologies, and creating inclusive decision-making spaces that empower women in value chains. Flexible training, localized communication, and participatory processes that consider women's roles, responsibilities, and mobility constraints should be built into gender-sensitive systems. Integrating gender considerations into innovation design and dissemination is critical for achieving equitable, resilient, and sustainable transformations of smallholder systems in SSA.

4.5.2. Indigenous Knowledge Systems and Innovation Fit in Smallholder Livestock Systems

Indigenous Knowledge Systems (IKS) are vital for livestock management, adaptation, and livelihood resilience in smallholder livestock systems in sub-Saharan Africa (SSA). These knowledge systems are the result of long-term interactions between rural communities and their local environments and are embedded in cultural values, social institutions, and traditional ecological understanding. Indigenous knowledge provides local solutions for livestock breeding, animal health management, disease control, feed use, rangeland management, weather forecasting, and climate adaptation (Van Rooyen *et al*., 2021; FAO, 2023). IKS develops under certain environmental and socio-economic conditions and is of great importance in resource-poor smallholder livestock systems.

Traditional knowledge is often ignored in formal agricultural innovation systems, but it is important. Many new livestock technologies are developed within scientific frameworks that focus on standardized external knowledge and ignore local experiences and production practices. The result is a knowledge-based fitness gap, where technologies are not adapted to local ecological conditions, cultural preferences, and community decision-making systems. Hence, the external promotion of technologies may be inappropriate or infeasible for smallholder livestock farmers in this region.

Indigenous livestock breeds may be less productive in intensive systems but have valuable adaptive traits, such as heat tolerance, disease resistance, and resilience to feed scarcity (Herrero *et al*., 2021). Local systems of knowledge sharing and traditional animal health practices also provide low-cost, culturally relevant alternatives to formal veterinary services in many of the country's remote areas. If these practices are not adopted, the relevance and sustainability of livestock innovations may be at risk. Thus, Indigenous knowledge and scientific innovation can improve the contextual relevance, adaptability, and resilience of agricultural technologies. Blending scientific innovation with local knowledge can boost farmer trust and uptake of new technologies and help build more sustainable and climate-resilient livestock systems across SSA.

4.5.3. Integrating Gender and Indigenous Knowledge into Innovation Systems in Smallholder Livestock Systems

There is a need to develop more inclusive, participatory, and context-responsive innovation systems that actively integrate gender perspectives and Indigenous knowledge systems to bridge the fit gap in smallholder livestock systems. Traditional top-down approaches to disseminating technology are increasingly being replaced by participatory innovation models that emphasize co-design, collaborative learning, and stakeholder engagement. These approaches bring together farmers, researchers, extension personnel, policymakers, private sector actors, and local communities to co-develop, adapt, test, and disseminate livestock innovations relevant to local needs and production realities (Klerkx *et al*., 2022; Van Rooyen *et al*., 2021).

Participatory innovation platforms such as farmer field schools, innovation hubs, community-based livestock breeding programs, and multi-stakeholder learning networks have been found to be effective in improving technology relevance, ownership, trust, and adoption by small-scale livestock farmers. These approaches create space for marginalized groups, such as women and Indigenous knowledge holders, to be meaningfully included in innovation processes and to influence the direction of technology. By integrating gender perspectives and Indigenous knowledge systems into the livestock innovation process, we ensure that the technologies are socially accepted, culturally appropriate, environmentally adaptive, and responsive to the diverse socioeconomic realities of rural communities.

Gender-sensitive and knowledge-inclusive innovation systems also contribute to the wider goals of social equity, resilience, and sustainability in smallholder livestock production systems. Innovations in livestock development programs that address gender-based barriers and value indigenous knowledge have the potential to rebalance power relations, build local capacities, and improve the participation of marginalized groups. These approaches also contribute to the development of more resilient and adaptive livestock systems that can effectively respond to climate change, resource constraints, and market uncertainties.

In conclusion, to successfully close the fit gap in smallholder livestock systems, we must acknowledge that agricultural innovation is not just a technical process but rather a socially embedded system influenced by relations of power, cultural norms, institutional structures, and knowledge dynamics. Technologies co-developed with agricultural communities and based on local knowledge systems are more likely to be adopted sustainably, remain relevant over the long term, and generate scalable impacts. Therefore, gender and Indigenous knowledge systems must be integrated into agricultural innovation systems for the inclusive, equitable, and sustainable transformation of smallholder livestock systems in SSA.

4.6. Conceptualizing the Fit Gap in Smallholder Livestock Systems

4.6.1. Defining the Fit Gap in Smallholder Livestock Systems

The Fit-Gap concept provides an important framework for understanding the persistent disconnect between the design of agricultural innovations and their adoption in smallholder livestock systems in sub-Saharan Africa (SSA) (Figure 1). This points to a disconnect between the technical, economic, institutional, sociocultural, and environmental assumptions underpinning agricultural technologies and the realities confronting smallholder livestock farmers. The Fit-Gap, therefore, is not a failure of innovation per se, but a failure to fit technologies with the capacities, priorities, and adaptive strategies of the intended users.

The Fit-Gap exists within multiple interrelated dimensions. Economic Fit concerns the affordability of technologies and the financial risks involved in their adoption among resource-constrained farmers. Many livestock innovations involve large investments, recurring input purchases, or long-term financial commitments that may not be possible in the context of income instability and climate uncertainty. Institutional fit refers to the availability of extension services, veterinary support, infrastructure, credit systems, markets, and policy support needed for effective technology adoption. Weak institutional systems and poor services in rural areas often constrain the sustainability of livestock innovations in smallholder systems.

Socio-cultural fit is the extent to which technologies fit with local cultural norms, Indigenous knowledge systems, gender relations and community decision-making structures. Technologies that ignore these social aspects are often viewed as culturally inappropriate or practically irrelevant, leading to low trust and adoption rates among users. Environmental fit is the extent to which technologies are appropriate for local agroecological conditions characterized by climate variability, feed and water shortages, disease pressure, and resource constraints. Technologies developed for stable, resource-intensive systems often do not perform well in the highly variable environments typical of smallholder livestock systems in SSA. Together, these dimensions demonstrate that successful agricultural innovation is not only a question of technical performance but also of contextual compatibility with the wider realities of smallholder livestock production systems.

4.6.2. From Technology Push to Context Fit in Smallholder Livestock Systems

Technology-push approaches have dominated agricultural innovation systems in SSA in the past, with innovations developed in formal research institutions and transferred to farmers through centralized, top-down, extension systems. These approaches tend to emphasize technical efficiency, scalability, productivity gains, and standardization. They are often grounded in the assumption that farming conditions, institutional environments, and farmer capabilities are reasonably uniform across regions and communities. Consequently, traditional innovation systems have often failed to recognize the heterogeneity, complexity, and diversity that characterize smallholder livestock systems in SSA.

Supply driven innovation models have often worsened the Fit Gap by promoting "one-size-fits-all" technological solutions that do not adequately reflect local socioeconomic realities, cultural practices, environmental variability, and production constraints. In such systems, farmers are often perceived as passive recipients of innovation rather than active agents in the technology development and adaptation processes. Such a low level of farmer engagement reduces ownership, trust, contextual appropriateness, and longevity in the adoption of agricultural technologies. This is because many technically sound innovations do not make a meaningful difference to smallholder livestock systems, as they are poorly aligned with the needs, priorities, and risk management strategies of smallholder livestock producers.

In contrast, the context-fit approach considers the process of agricultural innovation as participatory, adaptive, and demand-driven, actively involving farmers and local stakeholders in co-creating technologies and solutions for local needs. Context-fit innovation systems are based on collaborative learning, stakeholder engagement, and iterative adaptation, whereby farmers, researchers, extension agents, private sector actors, and policymakers jointly design, test, refine, and scale innovations that respond to local needs. These approaches recognize the importance of incorporating indigenous knowledge systems, local production practices, socio-economic constraints, gender relations, and environmental variability into innovation processes. Context-fit approaches to innovation embed innovation within local contexts, thereby improving the relevance, acceptability, adaptability, and sustainability of agricultural technologies in smallholder livestock systems in developing countries, such as Ethiopia.

4.6.3. The Fit Gap in Smallholder Livestock Systems

Smallholder livestock systems are a good example of the Fit Gap in agricultural innovation systems in sub-Saharan Africa (SSA). These systems are characterized by low use of external inputs, reliance on indigenous livestock breeds, limited access to veterinary and extension services, informal markets, and high exposure to climatic and economic risks. Although much has been invested in modernizing livestock and developing technologies that enhance productivity, the extent of adoption of innovations such as improved exotic breeds, commercial feed systems, intensive production models, and advanced veterinary inputs by smallholder farmers is relatively low.

This limited uptake is often not a failure of technology but rather a failure to fit the context of the realities of smallholder livestock systems. Improved exotic breeds may do well under controlled conditions, but they require high-quality feed, intensive health management, reliable water supplies, and veterinary support, which are seldom available in resource-constrained rural environments. Likewise, commercial feeding systems and veterinary technologies remain prohibitively expensive or unavailable because of poor infrastructure and a lack of institutional support.

Many smallholder systems still have indigenous breeds of animals that are better adapted to local conditions than exotic breeds. These breeds are more drought tolerant, better heat stress tolerant, resistant to endemic diseases, better adaptable to poor quality feed resources and harsh environments and require low external inputs. The fact that they are still in use suggests that smallholder farmers in uncertain conditions are often more concerned with resilience, adaptability, and livelihood security than with maximum productivity.

Therefore, the Fit Gap in livestock systems requires a transition from productivity-centered innovation models to more adaptive, affordable, and context-responsive approaches. Re-packaging agricultural innovations to include climatic variability, institutional limitations, Indigenous knowledge systems, gender dynamics, and resource constraints is critical to improving technology adoption, strengthening resilience, and supporting sustainable livestock transformation across SSA.

4.7. Technology and Innovation Differentiation Across Stages of National Development in Livestock Systems

Figure 2 illustrates that the level of development of a country has a strong influence on livestock technologies and innovation systems because it determines the infrastructure, institutional capacity, market systems, financial resources, and technological readiness. In low-income economies, where smallholder livestock systems dominate, innovations must be affordable, low-risk, labor-sensitive, and adjustable to resource constraints. Farmers often face limited access to credit, poor veterinary services, poor infrastructure, climate variability, and poor market integration. Thus, livestock technologies in these systems are targeted towards accessibility, resilience, and security of livelihood rather than sophistication.

In many sub-Saharan African (SSA) countries, livestock innovations are focused on practical and low-cost interventions, such as improved vaccination programs, affordable veterinary treatments, feed supplementation, climate-resilient breeds, community-based breeding, low-cost feed preservation, and mobile advisory services. These technologies are more compatible with the realities of smallholders; they require less capital, infrastructure, and technical expertise. As countries move into middle-income economies, innovation systems are increasingly adopting productivity-enhancing technologies, such as artificial insemination, improved feed systems, semi-intensive production models, digital advisory platforms, and electronic marketing systems, to increase commercialization and market participation.

In contrast, high-income economies have highly specialized, capital-intensive livestock systems supported by advanced infrastructure, digital connectivity, and strong institutions. These systems increasingly depend on artificial intelligence, automation, robotics, biotechnology, genomic selection, sensor-based monitoring, and precision livestock farming to improve their productivity and efficiency. However, these technologies require a substantial financial investment, the energy systems are unstable, and advanced technical skills are required. However, these are not feasible for smallholder systems in developing countries.

These differences illustrate the limitations of a 'one-size-fits-all' approach to livestock innovations. "Technologies that are effective in industrialized systems may not be suitable for the conditions of resource-constrained, climate-vulnerable smallholders." Thus, successful livestock innovation must be aligned with local socioeconomic realities, institutional capacity, agroecological conditions, and farmer priorities. The Fit-Gap framework shows that successful agricultural innovation depends on affordability, adaptability, resilience, and contextual relevance, not just technological sophistication.

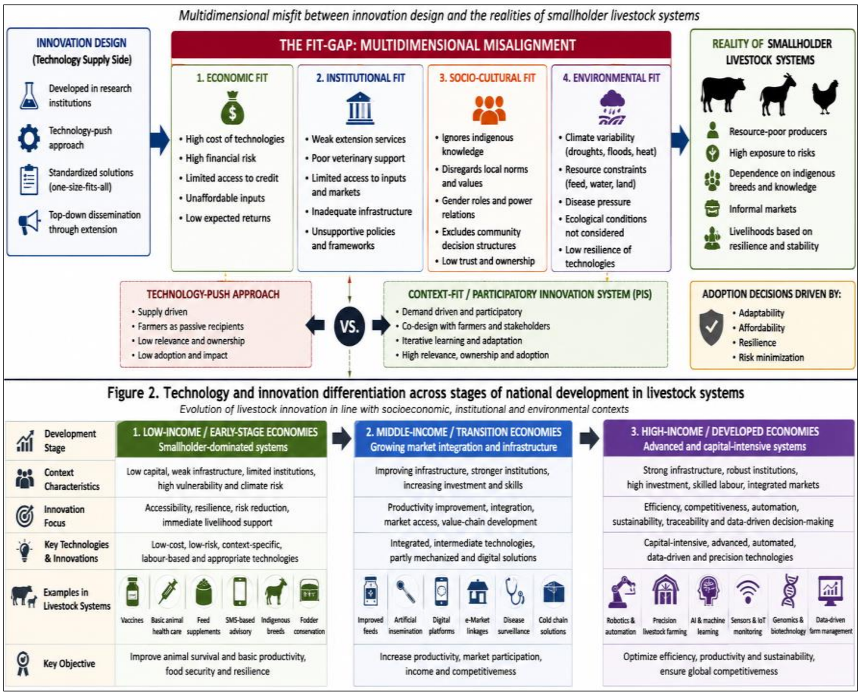

Fig 1:

4.8. Comparative Analysis: Zimbabwe and Selected SSA Countries

To provide empirical grounding for this study, a comparative analysis was conducted across selected Sub-Saharan African (SSA) countries, namely Zimbabwe, Kenya, Nigeria, Ethiopia, Ghana, and Zambia (Table 1). These countries represent different agroecological zones, livestock production systems, institutional arrangements, and pathways of agricultural innovation in SSA. The analysis is specifically of emerging livestock technologies and innovations in smallholder livestock systems, and it describes how the Fit-Gap appears differently across countries regarding economic, institutional, digital, socio-cultural, and environmental constraints. The selected countries also differ in terms of technological advancement, policy support, market integration, and climate vulnerability, which affect smallholder livestock production systems.

The comparison shows that the barriers to adoption are country-specific, but they always converge on four dimensions of the Fit Gap in smallholder livestock systems: economic, institutional, digital, and environmental. Economic misfits include the high costs of livestock technologies, limited access to credit, weak purchasing power, and high financial risk for smallholder farmers. Many livestock technologies (improved breeding, digital platforms) are not affordable for resource-constrained households, which constrains technology adoption across SSA. Institutional misfits include weak extension systems, fragmented policies, poor veterinary services, poor infrastructure, and limited coordination among stakeholders.

Table 1: Comparative Emerging Livestock Technology and Innovation Adoption Constraints Across Selected SSA Countries

Country	Dominant Smallholder Livestock System	Emerging Livestock Technologies and Innovations Promoted	Major Adoption Barriers	Major Climate and Environmental Stressors	Sources / References
Zimbabwe	Mixed crop–livestock smallholder systems	Climate-smart livestock practices, community-based breeding programs, feed supplementation, mobile livestock advisory platforms, vaccination programs	High input costs, limited credit access, weak extension systems, low digital access, climate variability	Droughts, erratic rainfall, pasture degradation, water scarcity	FAO (2023); African Union (2023); Choruma *et al*. (2024)
Kenya	Semi-commercial smallholder livestock systems	Mobile-based livestock advisory services, digital livestock marketing platforms, artificial insemination, improved dairy breeds, climate-smart feeding systems	Digital divide, gender inequalities, high technology costs, limited infrastructure	Floods, drought cycles, heat stress, feed shortages	Aker & Fafchamps (2022); Klerkx *et al*. (2022); World Bank (2021)
Nigeria	Smallholder and emerging commercial livestock systems	Feed supplementation technologies, mechanized feed processing, livestock vaccination campaigns, digital extension systems, improved breeds	Policy inconsistency, corruption, weak veterinary systems, poor subsidy targeting, limited market access	Flooding, desertification, rangeland degradation	World Bank (2021); FAO (2023); Barrett *et al*. (2022)
Ethiopia	State-supported smallholder livestock systems	Extension-driven livestock input packages, forage development, irrigation-supported livestock systems, artificial insemination, animal health campaigns	Top-down technology approaches, limited farmer participation, inadequate infrastructure, weak market integration	Recurrent droughts, feed scarcity, land degradation	Davis *et al*. (2022); FAO (2023); IPCC (2022)
Ghana	Market-oriented smallholder livestock systems	Improved feeding systems, livestock vaccination programs, digital livestock extension platforms, improved breeding systems	Affordability constraints, land tenure challenges, limited access to credit and extension support	Rainfall variability, heat stress, declining grazing resources	Ogutu *et al*. (2023); World Bank (2021); FAO (2023)
Zambia	Input subsidy-supported smallholder livestock systems	Farmer Input Support Programme (FISP), livestock vaccination programs, digital advisory pilots, improved forage technologies	Dependency syndrome, affordability challenges, low digital literacy, weak institutional coordination	Droughts, soil degradation, forage shortages	Nalwimba (2024); Choruma *et al*. (2024); African Union (2023)

In SSA, livestock innovation systems often lack farmer participation and local realities, thus limiting the adoption of technology. Digital misfits are important in current computing systems. Despite the potential of digital agriculture technologies, their adoption is hampered by poor infrastructure, unreliable electricity, low literacy, limited connectivity, and unequal access to devices, affecting women and marginalized groups. Environmental misfits are caused by a mismatch of technologies with variable agroecological conditions in SSA.

The suitability of technology is challenged by climate variability, droughts, feed shortages, land degradation, and the prevalence of diseases.

Technology adoption is affected by farmers' prioritization of resilience over productivity. Zimbabwe is a case of how all four Fit-Gap dimensions play out in smallholder systems. The livestock sector has weak extension support, limited financial inclusion, poor digital infrastructure, droughts, dwindling resources, and inconsistent policies, especially for resource-poor farmers.

Evidence suggests that the gap between policy frameworks and local production realities is to blame for this (Makoni *et al*., 2016). Zimbabwe is a case study of the role of systemic constraints in technology adoption and sustainability in SSA livestock.

4.9. Cross-Country Insights on Digital Livestock Technology Adoption Gaps

Digital agriculture and livestock-related technologies are increasingly promoted as tools to improve productivity, animal health management, market access, and climate resilience in smallholder livestock systems in sub-Saharan Africa (SSA). Innovations such as mobile advisory services, digital veterinary platforms, electronic livestock marketing systems, precision livestock technologies, and remote sensing tools can improve decision-making and disease surveillance and reduce transaction costs. However, the digital Fit Gap remains large across the SSA. The main drivers are poor digital infrastructure, low digital literacy, affordability, gender inequality, and weak institutional support systems.

The adoption of digital livestock technologies is context-specific and varies across countries based on infrastructure, institutional capacity, and socioeconomic conditions. Some countries have made progress in integrating digital agriculture, while others face structural barriers that limit the inclusiveness and scalability of digital innovation in rural livestock systems. For example, Kenya has pioneered digital agricultural integration with robust mobile networks and money systems to support livestock advisory and marketing platforms. However, costs, unequal access to devices, and gender inequality remain barriers to participation.

Conversely, countries such as Zimbabwe, Zambia, and Ethiopia face major digital infrastructure constraints, including poor connectivity, unreliable electricity, high data costs, and weak extension support. More sophisticated digital tools are often not appropriate for many rural farmers who do not have smartphones, Internet access, or digital training (Table 2). Digital tools, such as SMS-based advisory services, radio programs, and voice-based systems, are often more appropriate. Nigeria and Ghana have growing digital ecosystems; however, policy inconsistency, infrastructural disparities, and affordability issues hinder adoption.

In summary, the evidence suggests that digital livestock technologies must be compatible with local infrastructure, user capacity, institutional systems, and socio-economic realities. Investment in rural connectivity, affordable technologies, digital literacy, gender-inclusive approaches, and stronger extension systems are key to closing the digital Fit Gap and improving the accessibility and sustainability of digital innovation within smallholder livestock systems across SSA.

Table 2: Digital Livestock Technology Readiness and Adoption Constraints in Selected SSA Countries

Country	Digital Infrastructure for Livestock Systems	Adoption Level of Digital Livestock Technologies	Major Constraints	Emerging Opportunities	Sources / References
Zimbabwe	Moderate but strongly urban-biased	Low–moderate	High mobile data costs, low digital literacy, weak rural connectivity, limited extension integration	SMS-based livestock advisory systems, hybrid digital-extension models, mobile veterinary information systems	Choruma *et al.* (2024); African Union (2023); FAO (2023)
Kenya	Relatively advanced digital ecosystem	Moderate–high	Gender digital divide, unequal access to devices, affordability barriers among rural livestock farmers	Mobile money integration, digital livestock marketing platforms, e-extension services, climate-smart livestock apps	Aker & Fafchamps (2022); Klerkx *et al.* (2022); World Bank (2021)
Nigeria	Expanding but uneven digital infrastructure	Moderate	Weak rural infrastructure, policy inconsistency, poor institutional coordination, affordability challenges	Agri-tech startups, private sector digital livestock innovation, e-commerce livestock platforms	Barrett *et al.* (2022); World Bank (2021); FAO (2023)
Ethiopia	Limited digital infrastructure	Low	State-controlled telecommunications systems, low connectivity, institutional rigidity, weak digital access	Integration of digital tools within public livestock extension systems, government-led digitalization initiatives	Davis *et al.* (2022); FAO (2023); IPCC (2022)
Ghana	Growing digital infrastructure	Moderate	Affordability limitations, uneven rural access, digital skills gaps	Youth-driven digital entrepreneurship, digital livestock advisory systems, market information platforms	Ogutu *et al.* (2023); World Bank (2021); FAO (2023)
Zambia	Moderate but limited rural penetration	Low–moderate	Low awareness, weak digital literacy, limited outreach capacity, poor connectivity in livestock-producing areas	SMS-based extension services, digital extension pilots, mobile livestock information systems	Nalwimba (2024); Choruma *et al.* (2024); African Union (2023)

4.10. Input-Intensive Technologies: Economic Feasibility Constraints in Smallholder Livestock Systems in Africa

Modern livestock innovations and smallholder farmers' financial realities are characterized by major economic misfits that hamper the adoption of input-intensive livestock technologies in sub-Saharan Africa (SSA). Technologies promoted include commercial feeding systems, artificial insemination, veterinary pharmaceuticals, better breeding stock, mechanized feeding systems, and precision livestock tools to increase productivity, food security, and commercialization. However, their uptake is limited, as adoption decisions are strongly influenced by affordability, financial risk, climatic uncertainty, and access to institutional support.

Smallholder livestock farmers in SSA often face uncertain conditions, such as low income, weak market integration, climate variability, limited access to credit, and inadequate insurance systems. Hence, farmers often view new technologies in terms of livelihood security and risk minimization rather than productivity gains. Innovations that require high initial costs and ongoing purchases of inputs or specialized management are often seen as financially risky, particularly in drought-prone environments where feed shortages, disease outbreaks, and price fluctuations are common. Therefore, many farmers continue to use low-input livestock systems that may be less productive but are more resilient and carry less financial risk in uncertain conditions.

Table 3: Affordability and Risk Associated with Input-Intensive Livestock Technologies in Selected SSA Countries

Country	Access to Livestock Inputs and Technologies	Cost Burden	Risk Level	Adoption Trend	Sources / References
Zimbabwe	Limited access to commercial feed systems, veterinary inputs, improved breeding technologies, and digital livestock services	High	Very high	Declining or unstable adoption	FAO (2023); Choruma *et al.* (2024); World Bank (2021)
Kenya	Moderate access to improved livestock feeds, artificial insemination, vaccines, and digital livestock technologies	Moderate	High	Moderate adoption	Ogutu *et al.* (2023); Klerkx *et al.* (2022); World Bank (2021)
Nigeria	Subsidized access to livestock inputs, feed systems, and veterinary technologies	Moderate	High	Variable and policy-dependent adoption	Barrett *et al.* (2022); FAO (2023); World Bank (2021)
Ethiopia	State-supported livestock extension systems, improved feed technologies, veterinary services, and breeding programs	Moderate	Moderate	Relatively stable adoption	Davis *et al.* (2022); FAO (2023); IPCC (2022)
Ghana	Subsidized livestock production inputs, vaccination programs, and improved feed technologies	Moderate	High	Moderate adoption	Ogutu *et al.* (2023); World Bank (2021); FAO (2023)
Zambia	Subsidy-driven livestock input systems and digital livestock advisory pilots	Low–moderate	High	Dependency-driven adoption	Nalwimba (2024); Choruma *et al.* (2024); African Union (2023)

Table 3 the analysis reveals that the adoption of input-intensive livestock technologies in SSA is hampered by high costs, the absence of financial inclusion, climatic uncertainty, and market volatility. High start-up costs and limited access to cheap credit, combined with weak insurance systems and market fluctuations, increase the risk of adopting new technologies. Smallholder farmers are not adopting technologies that require high financial investments, especially in drought-prone areas where feed shortages, disease outbreaks, and variable livestock prices are the order of the day. Even with subsidies, uptake is fragile and subject to external support, as demonstrated in Zambia, Nigeria, and Ghana. Zimbabwe is a good example of how high input costs, limited access to credit, weak institutional support, and climate variability create high-risk environments for technology uptake. Ethiopia has a better extension system and adoption. There are concerns regarding the limited participation of farmers.

Technology adoption choices in SSA are linked to climate-related risks and economic constraints. Farmers are unwilling to invest in expensive technologies during droughts, volatile markets, or disease outbreaks if there is no guaranteed return or effective risk management. The findings suggest that low adoption levels are not necessarily due to farmers' resistance but rather a rational response to uncertain production settings. Data suggest that input-intensive livestock technologies are unlikely to be sustainably adopted without improved affordability, financial inclusion, climate resilience, and institutional support. (Barrett *et al.*, 2022; Forero 2025). Closing this Fit Gap will necessitate integrated, context-aware solutions comprising affordable technologies, improved credit and insurance systems, reliable veterinary support, climate-smart approaches, and better market integration for smallholder livestock farmers across SSA.

4.11. Policy Implications for Smallholder Livestock Systems

4.11.1. Shifting Toward User-Centered Innovation in Smallholder Livestock Systems

A major policy focus to address the Fit Gap in smallholder livestock systems in sub-Saharan Africa (SSA) is the transition from supply driven innovation systems to farmer-centered and participatory innovation approaches. Traditionally, livestock innovation systems have been top-down technology dissemination models, whereby technologies are designed and promoted by governments, research institutions, and development agencies, with little participation of livestock farmers in decision-making. However, there is growing evidence that participatory and co-designed innovation systems result in better relevance, ownership, trust, and long-term adoption of technologies by ensuring that livestock technologies are appropriate for the socio-economic conditions, cultural practices, environmental realities, and risk management strategies of the farmers (Klerkx *et al.*, 2022; Van Rooyen *et al.*, 2021).

This type of participatory approach is relevant in smallholder livestock systems, where farmers possess a rich body of context-specific knowledge concerning livestock breed adaptation, feed resource management, disease control practices, grazing systems, and climate adaptation strategies.

Therefore, Indigenous knowledge systems are important sources of practical expertise that should be incorporated rather than excluded from formal livestock innovation processes. Policies should encourage innovation systems in which farmers are active co-producers of knowledge and technology, not passive recipients of externally designed interventions.

Support from governments and development agencies in developing countries for multi-stakeholder livestock innovation platforms, farmer field schools, participatory research initiatives, and community-based breeding and livestock production programs can facilitate this transition. These partnerships foster adaptive learning, ongoing feedback, local experimentation, and co-development of technologies that are more suited to the realities of smallholder livestock systems in developing countries. Therefore, strengthening participatory livestock innovation systems is critical for improving adoption, resilience, and sustainability across SSA livestock sectors.

4.11.2. Strengthening Extension Systems in Smallholder Livestock Systems

In many SSA countries, livestock extension services are under-resourced, fragmented, understaffed, and ill-equipped to effectively reach geographically dispersed rural livestock farmers. Limited access to technical information, veterinary support, climate advisory services, and practical training on emerging livestock technologies and management practices in the livestock sector hinders farmers' ability to expand. Another important policy priority is to strengthen livestock extension systems to link livestock technology development with its practical application in smallholder production systems.

The integration of digital advisory tools into traditional face-to-face livestock extension systems provides important opportunities to improve the reach, efficiency, and timeliness of knowledge transfer. Hybrid livestock extension models that combine mobile phone advisory services, radio-based information systems, digital platforms, community demonstrations, and direct engagement with farmers can enhance accessibility without sacrificing trust, contextual relevance, or interpersonal learning relationships (Fabregas *et al*., 2020; Davis *et al*., 2022). These hybrid systems are especially useful in smallholder livestock systems, where digital infrastructure and literacy levels vary across communities.

There is also a need for concerted investment in improving human capacity development to enhance the effectiveness of livestock extension systems. Training of extension personnel on participatory methodologies, digital literacy, climate-smart livestock production, gender-sensitive approaches, and community engagement strategies is needed to equip them to better serve diverse smallholder livestock farmers. Policies should also promote pluralistic extension systems, including public institutions, private sector actors, farmer organizations, universities, veterinary service providers, and civil society organizations, to improve service delivery and ensure that livestock innovations are relevant to different farming contexts and production systems.

4.11.3. Promoting Inclusive Digital Technologies in Smallholder Livestock Systems

Digital agriculture and livestock technologies have the potential to transform smallholder livestock systems through enhanced access to information, markets, veterinary services, and climate advisory systems. However, persistent inequalities in affordability, connectivity, digital literacy, and access to digital devices continue to constrain the equitable distribution of these benefits among rural livestock farmers in India. Thus, policy interventions should aim at inclusive digitalization strategies that enhance the accessibility, affordability, and relevance of digital livestock technologies for marginalized groups, particularly women, youth, and resource-poor smallholder livestock producers.

Digital access in poorly connected rural communities can be greatly improved by promoting low-cost and user-friendly technologies such as SMS-based livestock advisory services, voice-enabled platforms, offline-compatible applications, and local language communication systems (Aker & Fafchamps, 2022; Baumüller, 2021). Digital livestock platforms should also incorporate indigenous knowledge systems, local cultural contexts, seasonal production calendars and locally relevant management information to increase farmers' trust, usability and practical relevance. Furthermore, improving the digital literacy of smallholder livestock farmers is a prerequisite for improving the effective use of technology in the livestock sector. Rural livestock communities can be provided with the technical skills required for engagement with emerging technologies through targeted training, community-based learning, and digital extension support systems. Overcoming gender inequality in the digital livestock innovation ecosystem. Women are often involved in livestock production but have limited access to mobile phones, the Internet, finance, and training on technical issues. As a result, inclusive digital livestock policies should be grounded in affordability, accessibility, gender equity, local relevance, and capacity building.

4.11.4. Enhancing Climate Resilience Through Emerging Technologies and Innovation in Smallholder Livestock Systems

With climate change exacerbating environmental variability and production uncertainty across SSA, building resilience within smallholder livestock systems has become a key policy priority. There is increasing recognition of the critical role of climate-smart and context-responsive innovations in livestock to improve adaptive capacity, reduce vulnerability, and enhance sustainable livestock production in the face of changing climatic conditions. Policy interventions should therefore prioritize targeted investments in climate-resilient livestock technologies and production systems, including drought-tolerant forage crops, resilient indigenous livestock breeds, climate-smart feeding systems, integrated crop–livestock systems, agroecological practices, and diversified livelihood strategies (Food and Agriculture Organization, 2023; Intergovernmental Panel on Climate Change, 2022).

Climate smart rangeland management, sustainable pasture use, rainwater harvesting technologies, integrated feed resource management, and diverse livestock production models that reduce dependence on climate-sensitive resources can improve resilience in smallholder livestock systems. Other services that are important in helping farmers to anticipate, adapt and recover from climate-related stressors such as droughts, disease outbreaks and feed shortages are climate information services, seasonal forecasting systems, livestock insurance mechanisms and early warning systems.

Policies should also encourage ecosystem-based livestock management approaches that promote biodiversity conservation, soil health improvement, sustainable grazing systems and long-term resource management. Therefore, the integration of climate resilience into wider livestock innovation systems is critical to ensure that new technologies and livestock production practices are sustainable, adaptable, and effective in the face of increasingly dynamic and uncertain environmental conditions.

5. Conclusion and Policy Implications

The study shows that the low adoption of agricultural innovations in smallholder livestock systems in sub-Saharan Africa (SSA) is less a function of the lack of technologies than the existence of a persistent "Fit Gap" between innovation design and the socioeconomic, institutional, digital, sociocultural, and environmental realities of smallholder farmers' lives. The results indicate that technology adoption is driven more by affordability, climate risk, institutional support, digital inclusion, and contextual relevance than by technical performance. Given climatic uncertainty, weak markets, and limited financial capacity, smallholder farmers generally tend to focus more on resilience, flexibility, and livelihood security than on productivity-maximizing technology.

The study further shows that technology-driven and top-down innovation models are insufficient for achieving sustainable livestock transformation in SSA. Instead, agricultural innovation systems need to be participatory, context-responsive, climate-resilient, and inclusive. This involves incorporating Indigenous Knowledge Systems, enhancing extension and digital support systems, improving access to affordable finance and insurance, and promoting low-cost climate-smart livestock innovations that are appropriate for resource-limited settings.

In conclusion, sustainable agricultural transformation in SSA will depend on redesigning innovation systems to develop new technologies and align with the realities, priorities, and adaptive capacities of smallholder livestock farmers. Therefore, closing the Fit Gap through inclusive and locally responsive innovation pathways is critical to improving technology adoption, building resilience, and promoting equitable and sustainable development of the smallholder livestock sector across SSA.

References

1. African Union. Africa agriculture development status report 2023: Building resilient agri-food systems in Africa. African Union Commission; 2023.
2. Aker JC, Fafchamps M. Mobile phone technologies and agricultural markets in developing countries. World Dev. 2022;157:105926. doi:10.1016/j.worlddev.2022.105926
3. Barrett CB, Benton T, Cooper K, Fanzo J, Gandhi R, Herrero M, *et al*. Socio-technical innovation bundles for agri-food systems transformation. Nat Sustain. 2022;5(8):641-648. doi:10.1038/s41893-022-00925-5
4. Baumüller H. The little we know: An exploratory literature review on the utility of mobile phone-enabled services for smallholder farmers. J Int Dev. 2021;33(1):134-154. doi:10.1002/jid.3524
5. Baumüller H, Hansen J, Byerlee D. Digitalization and smallholder agriculture in Africa: Challenges and opportunities for inclusive innovation. Electron J Inf Syst Dev Ctries. 2022;88(5):e12218. doi:10.1002/isd2.12218
6. Choruma D, Mapiye C, Nhamo N. Digital agriculture adoption constraints and innovation fit among smallholder farming systems in Southern Africa. Afr J Agric Res. 2024;20(4):233-247.
7. Davis K, Mekonnen DA, Spielman DJ. Strengthening agricultural extension systems in Sub-Saharan Africa: Evidence and policy implications. Agric Syst. 2022;198:103381. doi:10.1016/j.agsy.2022.103381
8. Doss C, Meinzen-Dick R, Quisumbing A, Theis S. Women in agriculture: Four myths. Glob Food Secur. 2020;16:69-74. doi:10.1016/j.gfs.2017.10.001
9. Fàbregas R, Kremer M, Schilbach F. Realizing the potential of digital development: The case of agricultural advice. Science. 2020;366(6471):eaay3038. doi:10.1126/science.aay3038
10. Finger R, Swinton SM, El Benni N, Walter A. Digital innovations for sustainable and resilient agricultural systems. Eur Rev Agric Econ. 2023;50(4):1277-1309. doi:10.1093/erae/jbad021
11. Food and Agriculture Organization. The State of Food and Agriculture 2023: Revealing the true cost of food to transform agrifood systems. FAO; 2023. doi:10.4060/cc7724en
12. Forero C. Economic risk, technology adoption, and resilience in smallholder livestock systems in Sub-Saharan Africa. Afr J Rural Dev. 2025;10(2):114-129.
13. Hammond J, Fraval S, van Etten J, Suchini JG, Mercado L, Pagella T, *et al*. The rural household multi-indicator survey: Assessing agricultural innovation and livelihood resilience in smallholder systems. Food Secur. 2020;12(4):867-880. doi:10.1007/s12571-020-01052-0
14. Herrero M, Thornton PK, Mason-D'Croz D, Palmer J, Bodirsky BL, Pradhan P, *et al*. Articulating the effects of food system innovation on climate resilience and sustainability in livestock systems. Glob Food Secur. 2021;28:100561. doi:10.1016/j.gfs.2021.100561
15. Intergovernmental Panel on Climate Change. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Cambridge University Press; 2022. doi:10.1017/9781009325844
16. Kiptot E, Franzel S, Degrande A. Gender, social networks, and agricultural innovation dissemination in rural Africa. J Rural Stud. 2021;83:221-230. doi:10.1016/j.jrurstud.2021.02.012
17. Klerkx L. Towards agricultural innovation systems 4.0: Supporting directionality, diversity, distribution, and democracy in food systems transformation. Wageningen University & Research; 2023. doi:10.18174/634949
18. Klerkx L, Begemann S. Supporting food systems transformation: The what, why, who, where, and how of mission-oriented agricultural innovation systems. Agric Syst. 2020;184:102901. doi:10.1016/j.agsy.2020.102901
19. Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming, and agriculture 4.0: New contributions and future research directions. NJAS Impact Agric Life Sci. 2022;94(1):100315. doi:10.1016/j.njas.2020.100315
20. Kok KPW, Klerkx L, *et al*. Addressing the politics of mission-oriented agricultural innovation systems. Agric Syst. 2023;210:103694. doi:10.1016/j.agsy.2023.103694
21. Makoni N, Mapiye C, Chikwanha O. Livestock innovation systems and adoption challenges among smallholder farmers in Zimbabwe. Trop Anim Health

Prod. 2016;48(6):1121-1130. doi:10.1007/s11250-016-1060-5

22. Metcalfe S. Participatory agricultural innovation systems and rural transformation in Sub-Saharan Africa. Agric Innov Rev. 2024;15(1):55-71.
23. Nalwimba N. Digital livestock extension systems and technology adoption among smallholder farmers in Zambia. Zambian J Agric Sci. 2024;12(1):45-58.
24. Njuki J, Pyburn R, Baltenweck I. Gender-responsive livestock development and innovation systems in Africa. J Rural Stud. 2022;91:231-242. doi:10.1016/j.jrurstud.2022.03.012
25. Nxumalo P. Emerging digital livestock technologies and smallholder adoption challenges in Southern Africa. J Agric Inform. 2025;16(1):77-93.
26. Ogutu SO, Qaim M, Mathenge M. Digital technologies, market participation, and smallholder agricultural transformation in Africa. World Dev. 2023;162:106122. doi:10.1016/j.worlddev.2022.106122
27. Rose DC, Sutherland WJ, Parker C, *et al*. Agriculture 4.0: Making it work for people, production, and the planet. Land Use Policy. 2021;100:104933. doi:10.1016/j.landusepol.2020.104933
28. van Rooyen AF, Homann-Kee Tui S, Nengomasha Z. Integrating indigenous knowledge systems into climate-smart agricultural innovation for smallholder systems in Africa. Sustainability. 2021;13(11):6144. doi:10.3390/su13116144
29. World Bank. Climate-smart agriculture in sub-Saharan Africa: Policies, practices, and technologies for resilience. World Bank; 2021. doi:10.1596/978-1-4648-1682-2