Harnessing Data-Driven Innovations for Climate-Smart Agriculture in East Africa

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Summary

Climate-smart agriculture (CSA) has emerged as a critical strategy for mitigating the impacts of climate change, particularly in East Africa, a region where agriculture is essential for food security and economic development. The integration of data-driven innovations, including remote sensing, machine learning (ML), artificial intelligence (AI), big data analytics, and the Internet of Things (IoT), is transforming farming practices by providing real-time data to optimize agricultural productivity, enhance resilience to climate impacts, and promote environmental sustainability. This review aims to evaluate the role of these technologies in advancing CSA in East Africa, focusing on their applications for managing climate variability, improving agricultural yields, and promoting sustainable farming practices. Quantified results from the reviewed studies show that smart irrigation systems, powered by IoT technologies, have improved water use efficiency by up to 30% in water-scarce areas of the region, while AI and ML models have increased crop yields by up to 40% in drought-prone areas. Despite these promising advancements, challenges such as limited technology access and affordability, digital literacy, policy gaps, integration barriers, and concerns around data privacy remain significant obstacles. The review further highlights key research gaps and offers recommendations for future research and development efforts to address these challenges and maximize the potential of data-driven innovations in CSA. In conclusion there is a need for continued investment in infrastructure, policy development, and capacity building to support the scaling up of these technologies across East Africa.

Key words

agricultural technology, climate resilience, climate-smart agriculture, data-driven innovation

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Received: April 6, 2025 | Accepted: October 15, 2025 | Online first version published: December 19, 2025

Introduction

Agriculture is the backbone of East Africa's economy, contributing significantly to employment, food security, and economic growth. However, East Africa's agricultural systems are under increasing threat due to climate change, characterized by erratic rainfall, prolonged droughts, and shifting agricultural zones (Tadesse and Abate, 2021). These climatic disruptions undermine food production, affecting both livelihoods and food security for millions of smallholder farmers, who account for the majority of agricultural producers in the region. Climate change coupled with the need for affordable, high-quality food, food security as well as a growing population have prompted the agriculture sector to incorporate technology into farm operations (Twetwa-Dube and Oki, 2023). In this view, climate smart agricultural technologies and practices can be one of the solutions for mitigating natural disasters and increasing agricultural productivity in East African countries (Ntawuruhunga et al., 2023). Climate-Smart Agriculture (CSA) has emerged as a framework that focuses on improving agricultural productivity, enhancing resilience to climate impacts, and reducing greenhouse gas emissions (Kihara and Nyaga, 2021). The CSA technologies and innovations help to improve the long-term viability and adaptability of agricultural systems (Mmbando, 2025).

The increasing adoption of data-driven technologies has the potential to revolutionize agriculture in the region, providing timely, precise, actionable information for better decision-making, and ultimately promote climate smart agriculture in the region. Technologies like remote sensing, machine learning (ML), artificial intelligence (AI), Internet of Things (IoT), and big data analytics are facilitating precision agriculture, where farmers can optimize resource use (e.g., water, fertilizers), monitor environmental conditions, predict weather patterns, and improve pest and disease management. By utilizing these technologies, farmers are better equipped to adapt to the unpredictable impacts of climate change, improve their productivity, and sustain agricultural ecosystems.

Despite their promise, the widespread adoption of these technologies in East Africa faces significant barriers, including limited access to technology in rural areas, digital literacy challenges, data privacy concerns, and the integration of complex data systems. Limited application of technologies and innovation, climate change, conflicts and rising food costs have hampered development and resilience building efforts in Eastern African countries. This suggests the need to apply data-driven agriculture through new technologies and innovations helps to support smallholder farmers in building their resilience, improving productivity, and ensure food security and nutrition. However, there is paucity of scientific information regarding the current state of knowledge on the application of data-driven technologies and innovations in East African region.

In this review paper, scientific information sourced from selected reputable journal articles and review articles primarily from electronic databases such as Scopus, PubMed, Science Direct, and Web of Science. Key search terms used included climate smart agriculture, remote sensing and geographical information system, data-driven innovation, agricultural technology, climate resilience, precision agriculture and IoT technologies. Thus, this review explores the role of data-driven innovations in CSA practices in East Africa, evaluating their impacts and identifying key challenges and opportunities for their future development and implementation.

Data-Driven Innovations in Climate-Smart Agriculture

Remote Sensing and Geographic Information Systems (GIS)

Advanced remote sensing technologies, including satellite imagery, drones and sensors, offer farmers real-time insights into weather patterns, soil health and crop dynamics. When integrated with Geographic Information Systems (GIS), these tools enable precise monitoring of land use changes, yield forecasting, and environmental conditions. By leveraging data-driven analytics, precision farming enhances resource efficiency, reducing waste while maximizing productivity (Mwega and Wambugu, 2020). Additionally, these technologies are vital for assessing crop health, detecting invasive weeds, and analyzing soil chemical composition and moisture levels (Niyonzima, 2024). Remote sensing, GIS, and Global Positioning Systems (GPS) have become essential in modern agriculture, transforming field analysis and mapping into highly efficient, data-driven processes (Ntawuruhunga et al., 2023).

These advancements are exemplified by the SERVIR program in East Africa, which uses satellite data to track land cover changes, provide early drought warnings, and enhance farming system resilience through localized weather insights and crop health assessments (Gebrehiwot and Haji, 2022). In Rwanda, GIS is employed to assess land suitability for climate-smart agroforestry (CSAF) by integrating environmental and socio-economic factors. This approach has enabled precise mapping of areas suitable for CSAF, supporting policy makers in making informed decisions to enhance ecosystem restoration, farm productivity, income generation, and food security (Ntawuruhunga et al., 2023.

Further case studies across East Africa proved the practicability of these tools. Using GIS and remote sensing in Kenya's Lower Eastern Region, lands have been identified for the right crops with the aim of future sustainable land-use planning (Ndungu et al., 2025). In Karamoja, Uganda, satellite-based methods have delivered essential information on drought status and food security to allow policy makers and farmers better choices (Nakalembe, 2022). In Rwanda, the combination of geospatial analysis with the Analytical Hierarchy Process (AHP) directs climate-smart agroforestry projects to the territories in which agroforestry can really increase resilience against climate shocks (Ntawuruhunga et al., 2023). On a regional scale, studies all through Ethiopia, Kenya, Uganda, and Tanzania stress that the synergy of GIS and remote sensing is crucial if climate-smart agriculture is to be scaled, giving the decision-makers tools that are evidence-based for monitoring, planning, and prioritizing interventions (Kirina, 2022).

Notwithstanding these benefits, uptake of remote sensing technologies in East Africa is hindered by very expensive implementation costs and the necessity to possess specialized skills in data processing and analysis (Niyonzima, 2024).

However, integration of remote sensing and geospatial information systems (GIS) with advanced analysis approaches stands at the essence of climate-resilient agriculture and thereby improving productivity, resilience, and sustainable natural resource management in the region at large.

Precision Agriculture and IoT Technologies

Precision agriculture, supported by IoT technologies, uses sensors and devices to collect real-time data on soil moisture, temperature, crop health, and weather conditions. This data allows farmers to optimize farming inputs, such as water and fertilizers, while increasing efficiency and reducing waste (Njoroge and Okello, 2022). It can also help to evaluate field variables such as biomass of plants or animals (Asfaw et al., 2019). Furthermore, this approach not only increases crop yields but also contributes to the long-term health of the environment by preserving natural resources and reducing pollution (Getahun et al., 2024). Several country-level experiences highlight both the opportunities and challenges of deploying these technologies in smallholder contexts.

Internet of Things (IoT)-based systems, such as soil moisture sensors, automated irrigation, and weather forecasting tools, enable site-specific farming interventions, enhancing water efficiency and reducing over-reliance on traditional farming techniques (Ntawuruhunga et al., 2023). In Kenya, smart irrigation systems using IoT-based sensors measure soil moisture and automate irrigation, improving water use efficiency by up to 30% in arid regions (Kihara and Nyaga, 2021). Similarly, farmers in Kiambu County, Kenya, reported that installing IoT soil sensors reduced water consumption by 20% while increasing crop yields by 15% (Kanake, 2016).

Further examples in East Africa illustrate the significant possibilities of these technological innovations. In Tanzania, IoT-based smart drip irrigation and fertigation prototypes for tomato cultivation combine soil moisture, temperature, and nutrient sensors with automated fertigation and irrigation systems. The prototype showed greater resource-use efficiency and higher yields compared to conventional irrigation methods (Ngoma et al., 2025). In Rwanda, IoT-based environmental observation systems in cassava farming support evidence-based fertilization and irrigation decisions and improve productivity and reduce post-harvest losses (Karerangabo et al., 2022). Ethiopian case studies further illustrate on-going integration of precision farming with IoT technologies. For example, farmers in rural areas and greenhouses have piloted smart irrigation systems equipped with soil moisture and climatic sensors to optimize the utilization of water and improve crop production (Azath et al., 2020). In regions like the Awash Basin and the Rift Valley, integration of AI and IoT technologies has reduced water usage while strictly enhancing productivity (Benti, 2024). With challenges ranging from high costs to limited digital infrastructure in place, the technologies represent a clean path towards realizing greater efficient, sustainable, and climate-resilient farming culture in the nation (Gebrekidan, 2020).

Artificial Intelligence (AI) and Machine Learning (ML)

Artificial Intelligence (AI) and Machine Learning (ML) models are increasingly used to predict weather patterns, detect pest and disease outbreaks, and forecast crop yields. By analyzing vast datasets, these technologies generate actionable insights that help farmers optimize planting schedules, resource applications, and pest management strategies. AI-powered platforms also integrate environmental and market data, supporting holistic farm management decisions (Njoroge and Okello, 2022).

Across East Africa, the farm sector is now embracing artificial intelligence (AI) to optimize farm output and mitigate the effects of climate change. For example, in Uganda, the FarmRise platform in use utilizes machine learning to analyze climatic conditions, soil health, and crop vigor and hence provides customized advice to farmers on planting time, irrigation regimes, and harvest time (Tadesse and Abate, 2021). Similarly, in Kenya, the Virtual Agronomist and PlantVillage platforms have used AI to provide farmers with fertilization, pest management, and disease advice to improve yields and at the same time minimize input costs (Foster et al., 2023). In Tanzania, the application of deep learning architectures, specifically Convolutional Neural Networks and Vision Transformers, has been used effectively to detect early outbreaks of Maize Lethal Necrosis and Maize Streak and hence undertake corrective actions to prevent losses in fields (Foster et al., 2023). These examples illustrate how AI and machine learning technologies not only provide farm-level productivity boosts but also scalable technology-based solutions to mainstream sustainable cultivation strategies across East Africa.

From an Ethiopian perspective, AI and ML are proving considerable value in areas of yield estimation and tracking. Guo et al. (2023) have shown how the integration of ground-truth information and Sentinel-2 satellite imagery with neural network predictions are able to accurately predict maize yields within smallholder farming systems and thus provide proof of concept of large-scale, high-resolution yield predictions. Correspondingly, Mondschein et al. (2024) mapped field-wise maize yields in Oromia using random forest regression in combination with vegetation indices such as NDVI and MTCI and achieved accuracies up to $R^2 = 0.63$. These proof-of-concept case studies underscore Ethiopia's growing contribution to the literature on AI-facilitated agricultural innovations using smallholder systems.

Big Data Analytics in Agricultural Management

Big data analytics enables farmers to aggregate and analyze vast datasets from diverse sources, including weather stations, sensors, market prices, and satellite imagery. This integration enhances resource allocation, risk management, and overall productivity. Additionally, big data supports policy makers in assessing agricultural sector needs and formulating targeted interventions (Mwega and Wambugu, 2020). In Tanzania, agricultural data platforms integrate weather patterns, soil health metrics, and market price fluctuations, empowering farmers to make informed decisions on planting schedules, pest control, and financial planning (Gebrehiwot and Haji, 2022).

Table 1 depicts the interconnected relationships among key technologies such as Remote Sensing, IoT, AI, and Big Data, and their respective impacts on CSA outcomes, including productivity, resilience, sustainability, and policy support. This visual representation illustrates how these advanced technologies enhance agricultural systems in East Africa by optimizing resource usage, improving climate adaptation, fostering environmental sustainability, and supporting data-driven policymaking. By mapping these connections, the figure underscores the essential role of digital innovations in transforming agriculture into a more efficient, adaptive, and climate-resilient sector.

Table 2 illustrates the relationships between technologies (Remote Sensing, IoT, AI, Big Data) and their impacts on CSA outcomes (Productivity, Resilience, Sustainability, Policy Support). It offers a visual overview of how each technology contributes to enhancing agricultural systems in East Africa.

Challenges and Barriers to Adoption

Digital Divide and Technology Access

Limited access to data-driven technologies in rural areas remains a significant barrier to the widespread adoption of these innovations. Challenges such as inadequate internet connectivity, electricity shortages, and low digital literacy hinder farmers from fully benefiting from these technologies (Gebrehiwot and Haji, 2022).

East Africa is confronted with a myriad of challenges in the adoption of digital agriculture technologies. Specifically, though Kenya has recorded significant achievement in the establishment of a digital landscape in agricultural solutions, inadequate internet connectivity, low levels of digital literacy, limited infrastructure coverage, and affordability challenges hinder digital technology adoption (Choruma et al., 2024). Likewise in Ethiopia, Uganda, and Tanzania, limited internet penetration and unstable electricity supply and the costly nature of digital equipment limit climate-smart agriculture adoption. Interestingly, low levels of digital literacy and widespread gender gaps hinder the adoption by farmers of digital media in the uptake of climate information, market information, and advisory services. Rural regions are even severely affected and exacerbated inequalities in technology adoption and participation. By and large, a significant percentage of farmers in the region possess low levels of technical proficiency to interact with digital products and services (Tamene and Ashenafi, 2022). Remedying these challenges calls for specialized intercessions and these may be in terms of infrastructure creation, affordable digital solution delivery, and intensive capacity-building (Gebrehiwot and Haji, 2022; Getahun, 2024; Manzoor et al., 2025).

Data Privacy and Security Concerns

Increasing digital agriculture technology usage among farmers has increased worries about data security and privacy (Tadesse and Abate, 2021). Case studies in Eastern Africa describe an array of challenges in these areas. For example, studies have found cyber security vulnerabilities in intelligent farming systems to include compromises of sensor information, broken cloud architectures, and attacks on digital identities (Alice et al., 2025). Additionally, cloud-based agricultural information systems face other vulnerabilities such as poor access controls and poor

Table 1. Impacts of Data-Driven Innovations on Climate-Smart Agriculture

Impact Area	Technologies Involved	Impact on Agricultural Practices	References
Improved Productivity	Precision Agriculture (IoT, Remote Sensing), GIS	Optimized resource use, increased crop yields through efficient water and fertilizer use	Tadesse and Abate, 2021; Mwega and Wambugu, 2020
Enhanced Resilience	AI, ML (Weather Prediction), Big Data	Improved adaptation to climate variability through timely decision-making and risk management	Kihara and Nyaga, 2021; Njoroge and Okello, 2022
Environmental Sustainability	IoT-based Smart Irrigation, Precision Agriculture	Reduced resource waste (water, fertilizers), promoting sustainable farming practices	Mwega and Wambugu, 2020; Kihara and Nyaga, 2021
Policy Support	Big Data, GIS, Remote Sensing	Data-driven policy design for climate-resilient agriculture and food security strategies	Njoroge and Okello, 2022

Table 2. The relationships between technologies (Remote Sensing, IoT, AI, Big Data) and their impacts on CSA outcomes (Productivity, Resilience, Sustainability, Policy Support)

Technology	Impact on CSA Outcomes	Reference
Remote Sensing	Improved monitoring of crops and climate conditions, enhancing productivity and resilience.	FAO, 2021
IoT	Real-time data collection from sensors, optimizing resource use for sustainability.	World Bank, 2022a
AI	Predictive analytics for better decision-making, supporting productivity and resilience.	CGIAR, 2023
Big Data	Large-scale data analysis for informed policy support and long-term sustainability.	African Union, 2023

regulatory enforcement that could diminish farmers' trust and limit technology adoption (Joshua, 2024).

Additionally, farmers' confidentiality and the establishment of sound data governance are in need of cooperation amongst several stakeholders such as technology vendors, governments, and farming organizations (Kaur, 2022). It has been suggested that farmers need absolute certainty in relation to data concerning farmers and farms being held safe from misuse or unlawful disclosure. The establishment of clear data-sharing agreements, well-established data ownership policies, and strong digital infrastructure is critical to establishing confidence and inducing the widespread adoption of these technologies amongst climate-smart farming organizations (Tadesse and Abate, 2021). Adoption of sound cybersecurity strategies such as end-to-end encryption and strong authentication procedures, enhancement of regulatory actions related to data safety, advancement in digital proficiency amongst farmers, and establishing mutually advantageous arrangements amongst key players are crucial in relation to preserving data security (Kaur, 2022; Joshua, 2024; Alice et al., 2025).

Integration of Disparate Data Systems

Integration of data across sources is among the governing challenges in utilizing data-intensive climate-smart agriculture innovations. The farmers and decision makers require diversified data sets like the weather forecasts, satellite imageries, and IoT readings but are often stored in non-compatible forms or by non-compatible institutions (Njoroge and Okello, 2022).

East Africa is home to numerous projects demonstrating the promise and challenges of mixing diverse sources of information. The Big Data initiative in Kenya is an applicable case. The Kenya Agricultural and Livestock Research Organization (KALRO) established it in partnership with the World Bank to bring together weather information, results of research, and market data and deliver real-time climate-smart guidance to smallholders. This level of juxtaposition facilitates immediate planting decisions, irrigation, and input management and raises productivity and enhances resilience to climate variability (World Bank, 2022b).

For the full realization of integrated data systems benefits, a few strategies are advisable. For example, the creation of platforms to collate and analyze such disparate data is needed in enhancing decision-making, usability, and digital agriculture tool effectiveness (Njoroge and Okello, 2022).

Policy Gaps for Data-Driven Innovations

Regardless of the big promise data-driven innovations bring in fostering climate-smart agriculture (CSA) in East Africa, a myriad of policy gaps remains in the way of their effective uptake. The coexistence of varied policies and inharmonious regulatory regimes creates impediments to the adoption of digital technologies in agricultural production (Mnukwa et al., 2025). Additionally, the failure to have unequivocal guidelines on matters of data ownership, secrecy, and sharing reduces farmers' confidence and will to adopt digital instruments (Chichaibelu et al., 2023). For Ethiopia in particular, the lack of sound frameworks on data governance has been identified as a discouragement to farmers adopting digital fixes and hence underscores the policy imperative in fostering adoption (Mazengiya, 2024). Moreover, efficient data sharing policies and operational frameworks in strengthening the collation and storage of data and enhancing accessibility in support of digital fixes in Ethiopia are nonexistent (Tamene and Ashenafi, 2022).

Likewise in Kenya, policy-based challenges such as poor coordination at the government agency level, poor support to rural ICT infrastructure, and poor consideration of gender and digital literacy challenges have hindered the adoption of digital agriculture technologies by smallholder farmers (Awuor and Rambim, 2022). The challenges are best addressed through coordinated effort by governments and other stakeholders through the creation of integrated national policies, investment in efficient rural digital infrastructure, establishment of sound data governance systems, and the delivery of specialized training programs to empower farmers to adopt these technologies in confident and efficient ways.

Affordability of Data-Driven Innovations

Affordability of data-driven innovations is a key factor in enhancing climate-smart agriculture (CSA) in the Eastern African countries. However, in this region, smallholder farmers are subjected to huge costs in buying and maintaining digital technologies, ranging from hardware to software and relevant training for efficient usage. In Ethiopia, limited access to credit and the high cost of digital devices hinder farmers from taking advantage of data-driven technology in enhancing CSA (Tamene and Ashenafi, 2022). Similarly, in Kenya, the high costs of digital platforms combined with low digital literacy and poor infrastructure restrict adoption of precision agriculture platforms by smallholder farmers (Awuor and Rambim, 2022). In Uganda, despite investments in digital agriculture, the lack of a coordinated strategy has led to high costs and reduced value as a result of fractured data and hindered scalability and sustainability (UNCDF, 2024). These challenges require implementation of focused policies to improve affordability, expanding digital infrastructure in rural areas, and providing capacity-building programs to farmers.

Connectivity Problem

Connectivity is one significant deterrent in the realization of data-driven innovations in climate-smart agriculture (CSA). Mmbando (2025) points out that in Sub-Saharan Africa and particularly in Eastern Africa nations, poor internet infrastructure, exorbitant connectivity prices, and inconsistent network coverage slow down the efficient usage of artificial intelligence and remote sensing technologies. These challenges impede farmers' uptake of real-time information on rain and temperature and market information and advisory services and therefore diminish the potential influence of digital innovations on agricultural resilience and food security. In Ethiopia, poor coverage in broadband and limited internet accessibility in rural areas hinder the real-time delivery of digital advisory services even with the expansive growth in ownership of phones (Tamene and Ashenafi, 2022). In Kenya, and in semi-arid and dry regions in particular, poor ICT infrastructure and unreliable internet connectivity are still discouraging the adoption of precision agriculture and a host of other digital innovations (Kilelu et al., 2019). Correspondingly, in Uganda, smallholder farmers face significant barriers to using ICT-based extension services due to limited rural network coverage, high costs of internet access, and low digital literacy, which collectively hinder the adoption of digital agricultural advisory tools (Kansiime et al., 2025).

Conclusion

Data-driven innovations are changing the face of climate-smart agriculture in East Africa, helping farmers boost productivity, adapt to climate change, and protect the environment. Technologies like remote sensing, IoT, AI, and big data analytics give farmers the tools they need to make smarter decisions and optimize their farming practices. But there are still challenges to overcome, such as limited access to technology, policy gaps, concerns about data privacy, and difficulties in integrating systems. To truly harness the potential of these technologies, it is crucial to address these issues. Investing in better infrastructure, improving digital literacy, and supporting research will be key to ensuring these innovations can help drive sustainable agriculture in East Africa for years to come.

Acknowledgements

The authors declare that there are no acknowledgements for this manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CREDiT Autorship Declaration

Dawit Mamo Zegeye: conceptualized the study, coordinated the review process, and drafted the initial manuscript. Additionally, Dawit conducted the literature search, contributed to the synthesis of findings, and critically revised the manuscript. **Assen Ebrahim:** provided expertise on the subject matter, contributed to the interpretation of the literature, and reviewed the final draft for important intellectual content. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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