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CLIMATE RESILIENT AGRICULTURE AND SCIENCE, TECHNOLOGY AND INNOVATION NEXUS FOR FOOD AND NUTRITION SECURITY IN UGANDA: A SYSTEMATIC REVIEW

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ABSTRACT

Purpose of the Study: The purpose of the study was to provide a systematic review analyzing the relationship between climate-resilient agriculture (CRA) and Science, Technology, and Innovation (ST&I) to enhance food and nutrition security in Uganda.

Problem Statement: Extreme weather and climate variability events are apparent in Uganda and indeed the Great Lakes region of Eastern Africa. The study recognised profound challenges that climate change presents to global food security and nutrition and emphasizing the need for climate-resilient agriculture driven by science, technology and innovation solutions.

Methodology: A systematic review approach was used to explore how science, technology and innovation (ST&I) and climate resilient agriculture (CRA) contribute to food and nutrition security. This methodology involved collection and synthesis of relevant evidence to address the study objectives based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach.

Results of the Study: The study found that science, technology, and innovation (ST&I) catalyze the transformation of agrifood systems, enabling improved food security and nutrition. The ST&I drives advancements in agricultural design, production techniques, recycling practices, and institutional frameworks, which enables the transition toward more resilient, efficient, and sustainable food systems where farmers are able to adapt to shifting climate patterns, securing long-term food availability. Technological innovations, including digital solutions, were recognised as key to enhancing food productivity, quality, diversity, and environmental sustainability when adopted by farmers. Other recognised benefits from the ST&I - driven climate-resilient agriculture solutions include; enhanced food security and nutrition through stabilizing yields, improving crop diversity and quality, improving crop resistance to adverse climatic conditions, reducing vulnerability to shocks, minimizing environmental impact, and strengthening livelihoods.

Conclusion: The study concludes that Uganda faces a critical gap in the documentation and evaluation of its diverse climate-resilient agricultural (CRA) innovations, despite Africa's abundance of such technologies. This lack of systematic knowledge hinders the effective deployment of CRA solutions tailored to local needs. Addressing food security and nutrition challenges requires leveraging science, technology, and innovation (ST&I)-driven mechanisms to integrate advanced research, innovative technologies, and context-specific practices. Farming is a knowledge drive enterprise and strengthening the capacities of smallholder farmers, who are central to Uganda's agriculture, is a priority. This entails targeted investments in training, infrastructure, and advisory services while addressing systemic institutional and policy barriers. Operationalizing the synergy between CRA and ST&I is essential for building sustainable food systems that enhance resilience to climate change, ensure food security, and promote improved nutrition in Uganda and elsewhere.

Recommendations: The study recommends boosting public investment in research and advisory services tailored to smallholder farmers' needs, alongside strengthening institutional frameworks through robust policies that address critical questions in the nexus between ST&I driven solutions for climate resilient agriculture, food security and nutrition. Prioritizing capacity-building initiatives and infrastructure development, such as irrigation, agroprocessing and storage systems, is essential for accelerating the adoption of CRA technologies hence strengthening food security and nutrition. To address the scarcity of peer-reviewed literature in Uganda, efforts should focus on generating research publications on CRA and ST&I nexus for food security and nutrition, effectiveness of CRA technologies, adaptation-community engagement strategies, building partnerships, and promoting participatory decision-making to enhance adoption of agricultural – climate innovations.

Keywords: *Agrifood systems, climate-resilient technologies, food productivity, sustainable development, technological innovations, Uganda*

INTRODUCTION

The 21st century is challenged with provision of safe, sufficient and nutritious food to the bulging world population, estimated at >40 billion people by 2050 (UN, 2014; Anand, 2017; Smith et al., 2024). This challenge is occasioned by several emerging and re-emerging issues, with climate change being prime to-date. Climate change affects food security and nutrition. Addressing climate change impacts require collective engagements and application of well-thought solutions based on science, technology and innovations. Over the past ten years, Climate resilient agriculture (CRA) has been and continues to be a pertinent strategy in addressing climate change impacts including food insecurity and nutrition (Viswanathan et al., 2020), while enhancing reduction in greenhouse gas emissions (Lamanna et al., 2016).

The strategy of CRA involves application of technologies to address food crises and livelihoods with minimal damage to environmental resources largely through a systems approach (agrifood systems) (Azadi *et al.*, 2021). However, the resilience and relevance of agrifood systems is strengthened by the application of ST&I-based solutions. For instance, genetic engineering, soil fertility improvement, and irrigation can effectively increase food availability; post-harvest and agro-processing technologies facilitate food accessibility, and biofortification enhance the nutritional value of food stuffs, which directly mitigates food instability and malnutrition (Anand, 2017; Moujabber et al., 2020; Viswanathan et al., 2020; Wakweya, 2023). Over the past ten years, CRA has evolved through different phases and several ST&I-based solutions for CRA have been developed across the world with varying levels of success (Kurniawan 2014; Sajid et al., 2024).

In Africa, the effective implementation of ST&I-based technologies for CRA is challenged by limited information to guide policy choices for adoption and application of the CRA innovations (Jasna et al., 2017; Cacho et al., 2020). The limited information on CRA technologies is a great challenge to most climate vulnerable countries bio economies. Uganda is one of the most climate vulnerable countries in Africa, and ranks 14th most vulnerable according to the ND-GAIN index (Chen et al., 2015). The country experiences significant variations in rainfall and temperature (Alupot et al., 2024; Oriangi et al., 2024). Changes in rainfall patterns and temperatures severally impact on agricultural productivity and food insecurity (Gebauer and Doevenspeck, 2015). Uganda's diverse topography, location, and susceptibility to extreme weather conditions and the country's efforts to address climate change impacts makes it a good case for climate related studies in the sub-Saharan Africa. Fortunately, Uganda's policy on science and technology emphasizes the need for scientific and technological innovations to improve the country's competitiveness in the global economy and support its social and economic development, as well as enhance climate change adaptation (Akali et al., 2024).

Although different CRA technologies are well documented in literature (Viswanathan et al., 2020), a systematic exposition of the role of ST&I and CRA contribution to food and nutritional security, and mechanisms for its effective adoption and implementation to strengthen food security and nutrition status of society particularly in the least developed countries is lacking. Yet, the absence of well-structured mechanisms thwarts efforts to guide policy makers and in strengthening the implementation of CRA interventions based on ST&I solutions. This review provides a reflection on CRA interventions and mechanisms for its adoption and implementation with special emphasis on Uganda. The specific objectives are to provide an exposition on the contribution of CRA innovations to food security and nutrition, analyze patterns in the adoption of CRA technologies, evaluate the barriers to effective adoption of CRA innovations, and synthesize strategic mechanisms to accelerate CRA technologies in Uganda.

CONCEPTUAL ANALYSIS

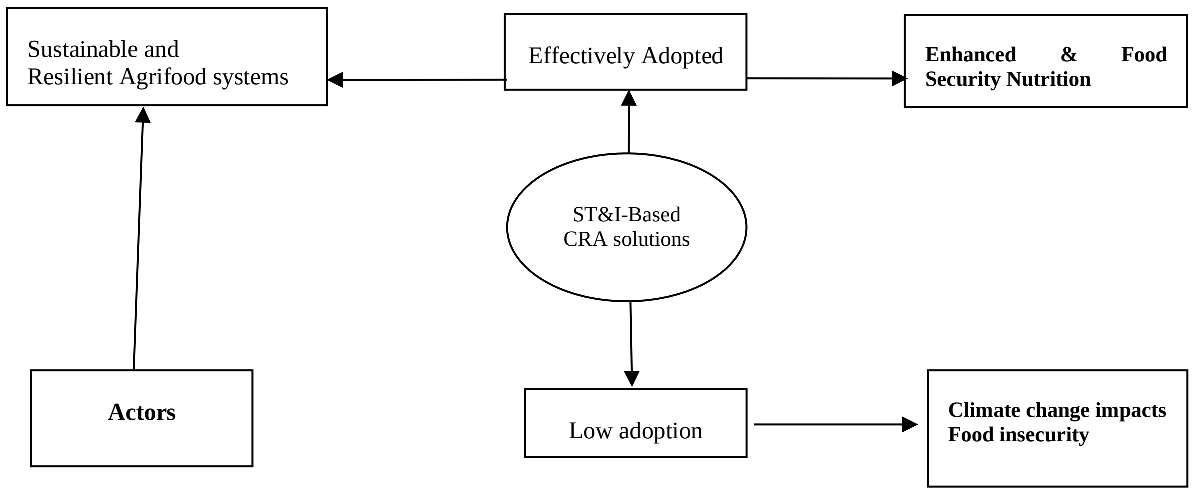

Figure 1: The relevance of ST&I based CRA solutions

MATERIALS AND METHODS

The study used a systematic review approach (SRA) as described by (CEE, 2018) to provide a reflective exposition of the strategies needed to accelerate the adoption of CRA innovations for improved food security and nutrition. The SRA provides a framework to address policy questions through gathering and synthesis of different findings combined to produce an outcome (Pearson, 2004; Liberati *et al.*, 2009; Pullin *et al*., 2009; Munn *et al.*, 2018). Also, systematic reviews convey the implications of best available evidence about complex questions by placing collected evidence in context, hence providing refined evidence to predict the outcome of alternative actions for effective decision making, assessment of intervention impacts, and the effectiveness of practices (Higgins et al., 2011; Aromataris and Pearson, 2014; CEE, 2018). This review identified studies focused on assessing the effectiveness of ST&I-based CRA solutions on food security and nutrition, and strategies to promote adoption of such CRA interventions in Africa, with a specific focus on Uganda.

The main research question was formulated to guide data collection and to inform policy, practice and further studies. Based on a human centered design thinking approach (HCDTA) (Garrette, et al., 2018), the key research question was: *"how might we promote climate resilient agriculture through ST&I based solutions to improve food security and nutrition?".* The HCDTA is one of the most appropriate approaches in solving human centered problems that are complex and poorly understood to be solved by conventional analytical approaches (Garrette, *et al.*, 2018). The main research question was subdivided into four sub-structured questions designed to; describe the contribution of CRA innovations to food security and nutrition; show continental patterns in the adoption of CRA technologies; explain the barriers to effective adoption of CRA innovations; and provide strategic mechanisms to accelerate CRA technologies in Uganda. The refinement of the open-ended questions into structured questions provided an opportunity to gather key units of evidence that can be combined to inform higher level decisions (Pullin *et al*., 2009). The evidence used to answer key questions in the study was entirely based on systematic synthesis of grey literature, scholarly publications, technical reports, and case studies across different countries globally.

Systematic review design

The review was confined to available publications within the last ten years (2014 to 2024). The concept of CRA has been evolving since 1997 when the first international meeting on climate change was held (Lipper and Zilberman, 2018). The consensus on promoting CRA practices gained more momentum in the last ten years (Lipper et al., 2018). Clearly, prior to 2014, no proper consensus on the strategic direction for CRA had been reached among key actors until the need for concerted efforts to address climate change impacts through sustainable approaches became evident (Lipper et al., 2018).

Search Protocol

The relevant studies were identified after through organised searching in electronic databases including PubMed, Google scholar, Scopus, Science direct, websites, use of reference lists, and individual searches in selected agricultural and policy journals. Across all databases, the following search terms were used: "effect of science and technology on climate resilient agriculture", CRA and food security", "CRA and human nutrition", "effect of CRA technologies on food security and nutrition" "global trends in adoption of CRA", "barriers to CRA adoption in Uganda", "The actors in CRA", and "strategies for adoption of CRA technologies".

The screening, exclusion and inclusion of evidences in the systematic review process followed the PRISAM ((Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach (Mckenzie *et al*., 2021). For inclusion, only studies with clear focus on the key elements within the main research question and the structured questions were considered. A similar criterion was applied to define the search key words. The screening of articles was stopped when the relevance of literature declines rapidly on preceding the initial articles in line with the search key words (CEE, 2018). The summary of number of included and excluded articles in the study are represented in Figure 2.

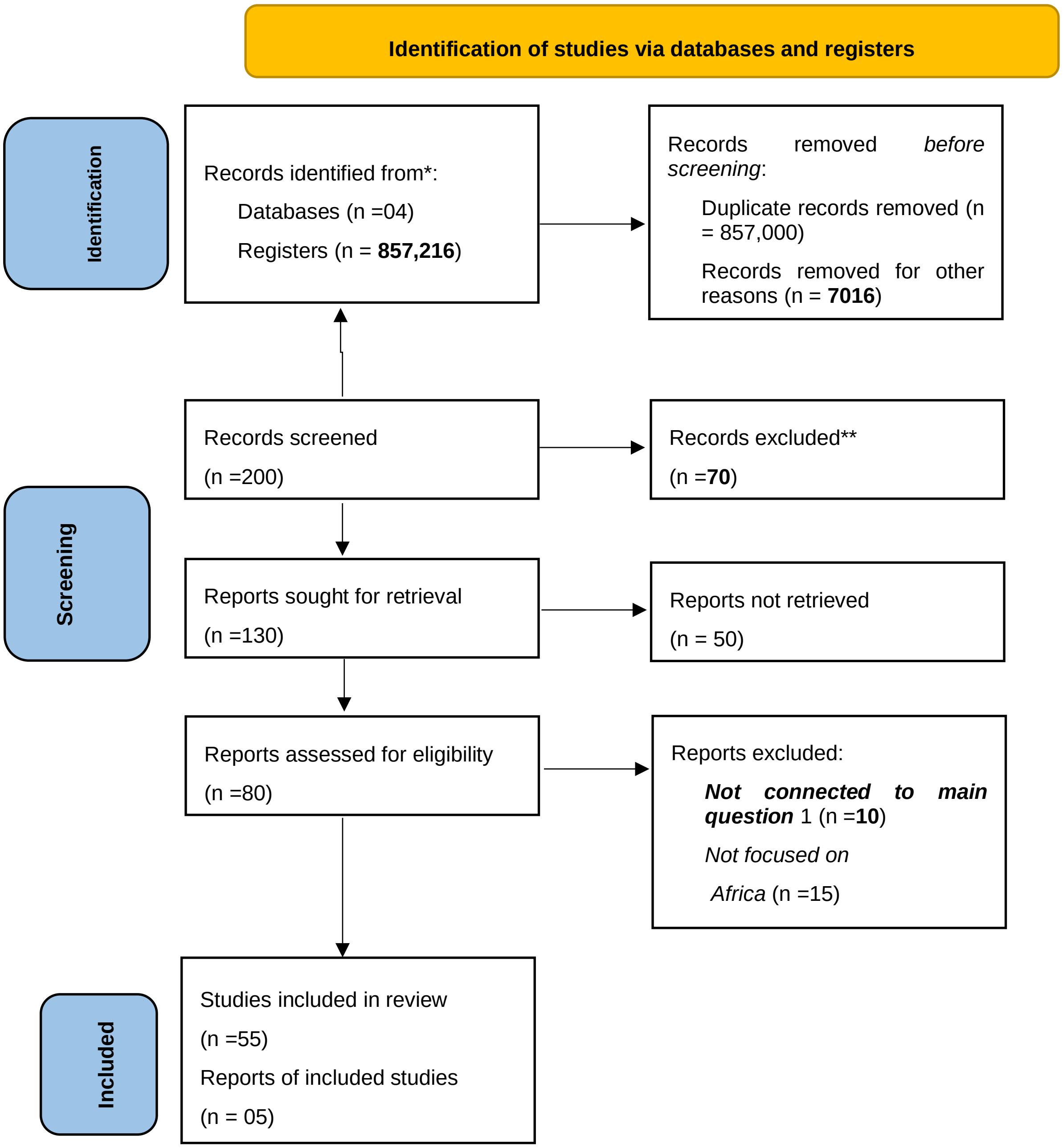

Figure 2: The inclusion and exclusion numbers

Eligibility criteria

The eligibility of searched evidence was premised on the logical flow of the retrieved article to respond to the key elements that explain the structure of research questions and the general study (ECC, 2018). The general thematic coding and data extraction followed critical steps in identification of patterns and themes (Braun and Clarke, 2006) which were refined further to provide a clear context of the data and in line with the need to answer the study questions. Finally, the number of articles collected, screened, included and excluded was recorded and summarised in a flow diagram as per expectations of the SRA approach (CEE, 2018). The final reporting of results was based on the objectivity of the findings as opposed to subjective advocacy of the CRA significance and barriers to its adoption by key stakeholders.

Summary of search terms used

This review used different search terms including; CRA, climate technologies, Innovations in agriculture, transformation of agrifood systems, barriers to climate resilient agriculture, as indicated in Table 1.

Table 1: Summary of Terms Used in Searching and Structuring of Review Questions

Population (P)	Intervention (I)	Comparator (C)	Outcome (O)
ST&I - based solutions for CRA	Promoting ST&I-based solutions for CRA Adoption in Uganda	Non-participating communities in CRA; Food security among communities before CRA	Environmental (Changes in food security dimensions, and nutrition; crop productivity) Socio-economic impacts: Livelihoods, Changes in farmers' income, food prices and nutrition status)
Keywords:	"Role of ST&I in climate resilient agriculture", CRA role in food security and human nutrition", "Role of CRA technologies in food security and nutrition", "Actors in CRA adoption", "Global trends in CRA adoption", "barriers to CRA adoption", "strategies for CRA adoption"		

Data from different electronic databases was organised in line with key elements in the structured questions and later summarised in excel sheets, short paragraphs, tables, and illustrations through figures. Presentation of results followed general summary of available information on CRA in a global context, Africa and Uganda in particular, highlighting specific theme such as; the contribution of CRA to food security and nutrition, barriers to adoption of CRA in Uganda and a synthesis of strategies for the effective implementation of ST&I-based solutions for CRA in Uganda as informed by findings in literature.

RESULTS

Information overview on ST&I, CRA technologies and Food security

Overall, the scientific literature of the existing technologies and innovations for climate resilient agriculture have been well documented in Africa. However, limited information is available on CRA technologies, their adoption levels and the role of science, technology and innovations in food security and nutrition in Uganda, as indicated in Table 2. Although Uganda shared 8.4% (8,614 articles) of the African published literature in Science Direct on climate technologies, not all the posted articles were relevant to the key elements in the main study questions and the structured questions as well. Hence, the non-focused published articles on the study questions were excluded from further analysis.

Table 2: Available Information in Literature

Database	No. of Records	% share of published information in Africa	Region/ Country	Search Terms
Science Direct	102,146	-	*Africa*	*Climate Technologies*
Science Direct	8,614	***8.4%***	***Uganda***	*Climate Technologies*
Science Direct	616	*14.1%*	***Uganda***	*Barriers to CRA*
Science Direct	4,293	-	*Africa*	*Barriers to CRA*
Science Direct	10,395	-	*Africa*	*CRA*
Science Direct	**1,335**	***12.8%***	***Uganda***	*CRA*
Science Direct	7,821	*75.2%*	South Africa	*CRA*
PubMed	*2,591*	*25%*	Kenya	*CRA*
PubMed	*47*	-	Africa	*ST&I in Food Security*
PubMed	***06***	***12.8%***	Uganda	*ST&I in Food Security*
PubMed	*409*	-	Africa	*CRA*
PubMed	**30**	***1.36%***	***Uganda***	*CRA*
PubMed	99	*26%*	Kenya	*CRA*
Science Direct	122,789	-	Africa	*Agric Technologies*
Science Direct	***11,617***	***9.4%***	***Uganda***	*Agric Technologies*
Science Direct	15,341	*22.3%*	Kenya	*Agric Technologies*
Science Direct	*3,369*	*78.5%*	South Africa	*Climate change adaptation technologies*
Science Direct	***623***	***14.5%***	***Uganda***	*Climate change adaptation technologies*
Science Direct	*1,210*	*28.2%*	Kenya	*Climate change adaptation technologies*
Google Scholar	*1,680,000*	-	Africa	*Role of ST&I in Climate adaptation*
Google Scholar	*160,000*	*9.5%*	Uganda	*Role of ST&I in Climate adaptation*
Google Scholar	*341,000*	*20.3%*	Kenya	*Role of ST&I in Climate adaptation*
Google Scholar	*32,100*	*32.6%*	Uganda	*Role of CRA Food security & Nutrition*
Google Scholar	*98,400*	-	Africa	*Role of CRA Food security & Nutrition*
Google Scholar	*45,600*	*45.5%*	Kenya	*Role of CRA Food security & Nutrition*

The evolution of CRA across the world

The concept of climate resilient agriculture (CRA) has evolved in four decades. The CRA emergence can be closely analysed within the ensuing developmental phases of climate change since the world climate conference in 1979, and the establishment of the International Panel on Climate Change (IPCC) in 1988 (Lipper and Zilberman, 2018). The subsequent events and actions that followed had directly impacted on the evolution and structuring of the climate resilient agriculture concept as illustrated in Figure 3 (Lipper and Zilberman, 2018). The subsequent events and actions that followed had directly impacted on the evolution and structuring of the climate resilient agriculture concept as illustrated in Figure 3 (Lipper and Zilberman, 2018).

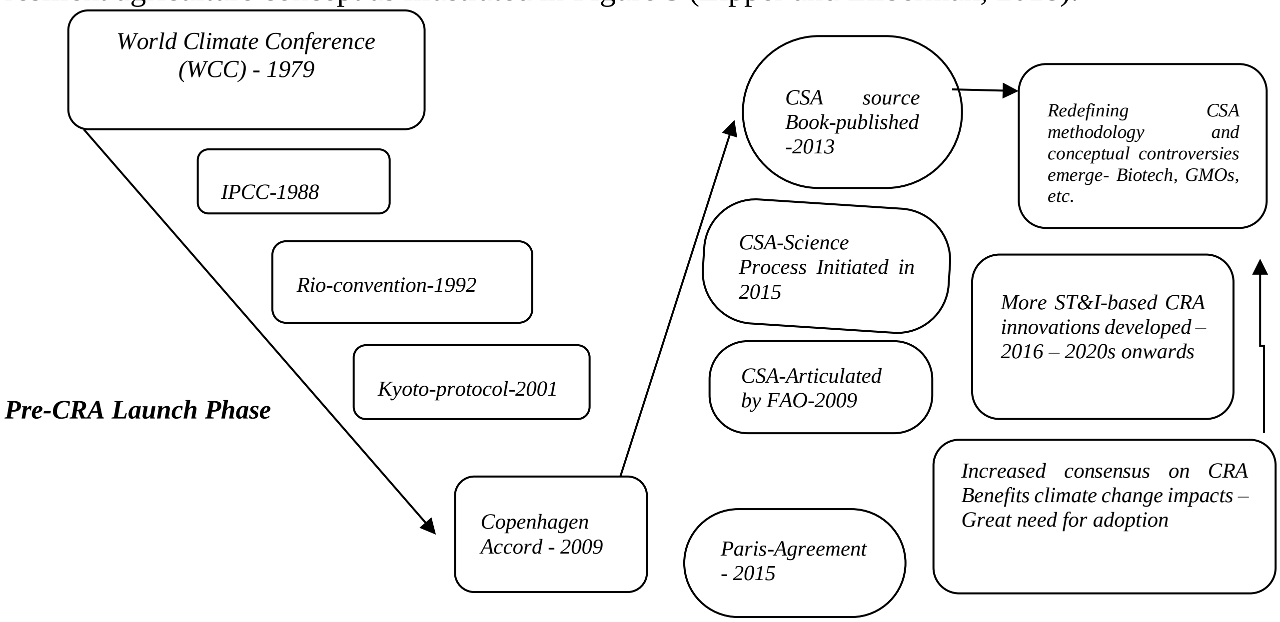

Figure 3: Schematic illustration of the CRA evolution as modified from (Lipper and Zilberman, 2018)

The role of CRA technologies in food security and nutrition

The CRA goals can be summed up into four areas of focus including; (i) agricultural productivity and income improvement, (ii) improving adaptability to climate change response, (iii) reducing greenhouse gas emissions, and (iv) evaluation of CRA impacts for better strategies. Table 3 summarizes evidence from literature on the components of ST&I - solutions and their contributions to food security and nutrition through the CRA framework (Table 3).

Table 3: CRA Goals and ST&I-Based Solutions

CRA Goal	ST&I innovations	Effects/benefits	References
Agricultural productivity & Income	Technology to: combat crop/animal stress improve crop/animal yield; improve Soil fertility /Water availability	Food production Increased	Reddy, 2015; Zong et al., 2022
	Technologies for proper food storage, Preservation, Transport and agro – processing	Food accessibility improved	Singh et al., 2022
Improving adaptability to climate change response	Applied sciences/Genetic engineering to produce High - nutrient crops	Combat malnutrition, improve food utilisation and use.	
Reducing green-house gas emissions	Technologies for climate change mitigation/ adaptation (precision agriculture)	Food instability addressed	Mustafa et al., 2021
	Carbon farming/ carbon smart farming, regenerative agriculture, and IoT smart farming techniques	Reduced inputs, lower greenhouse gas emissions	Panchasara et al.,2021

Several ST&I-based studies and initiatives have been established to address food security and nutrition issues across the world and most of them focus on crop diversification, precision agriculture techniques, weather forecasting, agroecological approaches, and genetic engineering or modification. conducted to address food security and nutrition challenges (Anandi, 2017; Sarma et al., 2024). The food security dimensions that require the application of science and technological innovations mainly include; food availability, access, food use/utilisation, and food stability. The ST&I applications should lead to improvements in food system components (farm – to - market), while addressing food security concerns and environmental sustainability. The challenges that require ST&I based solutions include; combating biotic and abiotic crop and animal stresses, raising health and productivity of crops and livestock, soil fertility improvement, water availability, and these collectively lead to increased food production.

Technologies focused on ensuring effective food storage, preservation, transport and agro-processing innovations help to address food accessibility, while the applied sciences help to produce high-nutrient crops hence combating malnutrition, improving food utilisation and use.

Some ST&I based technologies for climate change mitigation, and adaptation such as precision agriculture, index-based insurance, and early warning systems infer profound impacts on addressing food instability, and these have been identified with their associated challenges (Anand, 2017). These technologies range from ST&I applications that address crop productivity improvement, crop resistant varieties, livestock agriculture improvement, lack of water availability, soil health, precise integration and scheduling of inputs, urban farming, power and control-intensive operations, post-harvest losses, agroprocessing equipment, lack of nutritious foods and limited diet information, inability to predict when and how to do farming, and poor financial mechanisms for household income (Anandi, 2017).

Most studies agree that ST&I based solutions for climate change mitigation and adaptation should focus on strategies for effective information provision and knowledge transfer, while taking into consideration the social, as well as technical, innovations. Hence the CRA practices should provide multiple effects and benefits so as to increase their capacity for diffusion and adoption by majority of actors in the operation of sustainable Agrifood systems, while offering increased resilience, mitigation and adaptation to climate change impacts. For instance, while the use of big data and the Internet of things for accurate agriculture is commendable, the same solutions can be harnessed for additional agricultural applications, such as farmer decision support, precision farming, and insurance.

Although different sustainable agro-based issues continue to be discussed at the global, regional and national levels, prominent challenges for developing countries may involve the innovation capacities to assess, select, diffuse, adapt, and evaluate such technologies to address local agricultural challenges, owing to the knowledge intensity of modern agricultural biotechnology (UNCTAD, 2002). These innovation capacities involve not only human capital, research and development institutions, and enabling infrastructure, but also legal and regulatory policies that promote trade and innovation, recognize traditional and indigenous knowledge, and establish biosafety regulations and institutions that ensure human, plant, animal, and environmental safety (UNCTAD, 2004). In summary, the contribution of ST&I-based solutions to food security and nutrition can be understood in the context of what CRA goals and climate change effects in general.

Innovations for agrifood systems transformation in Uganda

There is evidence of extreme weather and climate variability events in Uganda and the Great Lakes region, including Lake Victoria, that reveal a pattern of increasing frequency and intensity of such events. For instance, Studies have shown that extreme rainfall events have become more frequent and intense over the years. For the period from 2011 to 2022 a notable increase in extreme rainfall events, with October consistently recording the highest count of extreme rainfall days has been reported (Badolo and Kinda,2012; Ariong, 2012). According to World Bank (2024) various climate indices, such as the Consecutive Wet Days (CWD) and Consecutive Dry Days (CDD), have shown significant trends.

The CWD index has decreased in 72% of the stations analyzed, while the CDD index has increased in 44% of the stations. The distribution of extreme rainfall events is not uniform across the region. Eastern Uganda and areas around Lake Victoria have experienced more intense and frequent extreme rainfall compared to other regions (Nuwagaba and Namateefu, 2013; Kagorora et al., 2021). Climate change has played a significant role in the increase of extreme weather events. Warmer temperatures increase the potential for air to carry moisture, leading to heavier precipitation (Barungi, 2022). Historical data from 1981 to 2022 has been used to analyze the frequency and pattern of extreme rainfall events. These data have and continue to help in understanding past trends and planning for future adaptation and mitigation measures (Bamanyaki, 2020).

Available evidence indicates that climate change has had significant impacts on food and nutritional security in Uganda (FAO, 1996; 2007; 2008; Thompson et al., 2010; Dale et al., 2015; Wambede and Mukooli, 2017; Watala, 2017; Byaruhanga, 2018) . Key areas highlighted in literature include:

- Crop yield reduction: Changes in temperature and precipitation patterns have led to reduced crop yields. For instance, maize and beans, which are staple foods in Uganda, have been particularly affected.
- Water scarcity: Increased temperatures and erratic rainfall have resulted in water scarcity, affecting both crop irrigation and livestock. This has led to decreased agricultural productivity and food shortages.

- Nutritional deficiencies: The reduction in crop yields and livestock productivity has led to nutritional deficiencies among the population. Malnutrition, especially among children, has become a significant concern.
- Pest and disease outbreaks: Climate change has also contributed to the spread of pests and diseases, further impacting crop and livestock production.
- Floods and landslides: Areas that have received heavy rains have experienced flooding and landslides. These have been very disruptive to human settlements and particularly the smallholder farming that has been totally disrupted.

Climate change impacts necessitate interventions to mitigate effects. Over the years, several innovations have been developed to strengthen agrifood systems, in line with sustainability principles under the full context of sustainable development. The need to transform agrifood systems is premised on the fact that climate change impacts have significantly changed the stability of food security dimensions and livelihoods. Ironically, agriculture is a key source for greenhouse gas emissions, due to its direct and indirect impacts towards climate change which is exacerbated by greenhouse gas emissions (Pancharasa et al., 2021).

The effort towards effective transformation of agrifood systems for sustainability should therefore consider those innovations that can generate changes in design, production, recycling, and institutional mechanisms that foster transitions towards sustainable systems. The key strategies, means and outputs from intentional agrifood systems transformation are illustrated in Table 4. It is believed that effective application of the suitable strategies, through appropriate means can provide sustainable outputs with multiple benefits to food security, reduced climate change impacts and overall cohesiveness among the key actors in the agrifood systems (Larsen et al., 2009). Science, technology, and innovations (STI) can play a crucial role in mitigating effects of climate change and variability to food and food and nutritional security (World Bank Group, 2021; Zewdie, 2014). Examples of STI driven interventions include among others, the following:

- Climate-resilient crop varieties: Developing and promoting the use of climate-resilient crop varieties can help farmers adapt to changing climatic conditions. These crops are more tolerant to drought, heat, and pests.

- Improved irrigation techniques: Implementing advanced irrigation techniques, such as drip irrigation and rainwater harvesting, can help conserve water and ensure consistent crop growth.
- ICT for market access: Utilizing information and communication technology (ICT) can improve market access for farmers. This includes providing real-time market prices, weather forecasts, and agricultural advice through mobile phones and radio.
- Agroforestry and sustainable practices: Promoting agroforestry and sustainable agricultural practices can enhance soil fertility, reduce erosion, and increase biodiversity, leading to more resilient food systems.
- Research and Development: Investing in research and development can lead to innovative solutions for food security, such as new crop varieties, pest-resistant technologies, and efficient farming practices.

Table 4: Key Strategies in Agrifood Systems Transformation

Strategy	**Actors**	**Benefits/Outputs**
Redesign the research agenda to focus on smallholder farmers needs	Research centers, Researchers, education institutions	Wider engagement of key actors in sustainable agrifood systems
Investing in human capacity	Local government, international	Enhanced diffusion and adoption of new innovations
Enabling infrastructure for food systems	International/National level	Effective implementation of key innovations
Establish governance structures to enhance agrifood systems transformation	International/regional/National	Effective coordination of actors
Strengthening knowledge flows between farmers and scientists	International/regional / National level engagement	Enhanced diffusion and adoption of technologies

The transformation of agrifood systems to more sustainable models should preferably support pro-poor and cost-effective agricultural innovations, effective engagement of smallholder farmers, make use of local and traditional knowledge systems, enhance gender equity and be linked to commercial empowerment and livelihoods of farmers. Therefore, this kind of transformation require several strategies to design specific research agenda that will address the critical needs of smallholder farmers (SHFs), as these constitute the largest portion of actors in the agrifood systems, especially in the developing countries, and yet suffer more consequences from climate change impacts. The deliberate investment in human capacity through training, capital enhancement, and technical empowerment of the actors with skills and knowledge for sustainable agrifood systems is also needed to enhance diffusion and adoption of new innovations. Also, the availability of relevant infrastructure such as roads, accelerates technology adoption, transport of goods and delivery of agricultural produce to markets which eases, the implementation of key innovations.

Infrastructure also reinforces the impact from appropriate governance structures in catalyzing agricultural innovation and strengthening knowledge flows between farmers, scientists, research and education institutions, firms such as agricultural producers, inputs suppliers for, processors, distributors, agricultural extension services providers, government ministries, international agencies, NGOs, retailers and wholesalers (Larsen et al., 2009). Designing and strengthening an agricultural innovation system involves promoting research and development, investing in infrastructure, building human capacity, creating an enabling environment and strengthening knowledge flows, particularly among scientists and farmers. Since women account for a substantial segment of agricultural labor, a gender-sensitive lens should be applied to agricultural innovation.

The investment in high-quality research that is coherent with production models adapted to the needs of smallholder farmers is also critical. There is need to invest in breeding programmes and support for local seed systems that allow the diffusion of locally adapted genetic material, which farmers would have the right to easily share and market. While science can play a key role in developing adapted technologies, ST&I in support of context specific needs of smallholder farmers and beyond the production remains essential. Finally, the development of sustainable agricultural systems is achievable especially when effective governance mechanisms are in place and policy coherence is fostered between sustainable agricultural development, food systems, environmental concerns, social protection, education, nutrition and health policies and programmes, as well as between their respective institutions, agencies and ministries at the national and international levels

Technological innovations for Climate-resilient agriculture in Uganda

Following the global consensus on the role of CRA to insulate society from several disastrous impacts of climate change, a number of technological innovations have been developed for CRA to strengthen food security, resilience, and adaptability to climate change impacts. Overall, the old, emerging and new technologies for CRA can be classified into three classes within the context of CRA goals, namely: (i) technological innovations to promote agricultural productivity and income, (ii) innovations for improving adaptability and mitigation to climate change response, and (iii) innovations to enhance reduction of greenhouse gas emissions. The CRA strategies have a direct bearing on sustainable food production and security and enhancing the resilience of farmers against climate-induced impacts (Sarma et al., 2024).

Numerous studies have established technological innovations that enhance CRA (Baliwada et al., 2014; Reddy et al., 2018; Rana et al., 2018; Harikrishna & Naberia, 2021;). In addition, the CRA framework and assessment of indicator system is also documented (Zong et al., 2022). For instance, CRA technologies developed in India include; microbial technologies to rejuvenate crop productivity, integrated pest management strategies, resource conservation strategies, improved cropping system adaptable to climate change, integrated farming to minimize risk under climatic change scenarios, nutrient management strategies to increase rice production, food processing technologies, suitable mechanization strategies for small-holder farmers, high crop yielding varieties, integration of crop farming, livestock and agroforestry, and strategies to disseminate emerging varieties for farmers (Tripathi and Bisen, 2019).

In Uganda, most of the existing CRA technologies range from post-harvest technologies, infrastructure design, biogas, and indigenous knowledge practice such as terracing, and (Bendito, & Twomlow, 2015; Taremwa et al., 2016; Kandulu et al., 2024), include; CRA technologies are designed to focus on strategies that minimize climatic change risks (Sreenivasulu et al., 2014; Bhandari et al., 2024; Cabusora, 2024), such as diversification of crops, developing environmental specific varieties such as drought resistant crops, and resistant crops in water logging, soil cover protection, precision agriculture, strategies to enhance resilience of agricultural production to climate change, weather forecasting, genetic engineering, effective water management, and agroforestry (Heinz et al., 2024; Sarma et al., 2024).

Table 5: Summary of Technological Innovations for CRA

Challenge addressed	CRA technological innovations	References
Climate change resilience Climate risk mitigation Agricultural productivity Price fluctuations Environmental specific characteristics Food security Nutrition status	Resistant climate specific varieties Crop diversification/Carbon reduction strategies Soil enhancement/Crop variety improvement Policy innovations/Market access strategies Resistant varieties Increased agricultural productivity/b Biofortification through genetic engineering	Langridge et al., 2021 Chen et al., 2021 Reddy et al., 2018 Dhanker and Foyer, 2018

The review findings highlighted more strategic innovations developed to strengthen agricultural productivity, climate resilience, carbon reductions, climate risk mitigation, addressing environmental specific characteristics and food security. However, less technological innovations tend to focus on addressing challenges related to human nutritional security (Reddy, 2015). In addition, the review findings indicated a growing consensus that addressing food security and climate resilient agriculture is goes beyond establishing technologies for increased agricultural production and productivity, and food security. Effective strategies should wholistically engage policy actors, political actors, institutional and different networks at various scales of engagement including national, regional and global networks, to effectively address the climate change risks and challenges (Zong et al., 2022).

Adoption patterns for CRA technologies in Uganda

Since the onset of climate change mitigation efforts, greater emphasis has been placed on clarifying methodologies and approaches for implementing Climate-Resilient Agriculture (CRA), with relatively less focus on encouraging its adoption. This imbalance has contributed to low adoption rates of CRA strategies among key actors. Globally, the adoption rate of CRA strategies was estimated at just 1% per year between 1999 and 2014, with faster adoption observed in some developing countries under exceptional circumstances (Campbell and Thornton, 2014). In Sub-Saharan Africa (SSA), adoption of climate-smart agricultural practices (CSAPs) remains particularly low (Campbell and Thornton, 2014; Ogisi and Begho, 2023).

In Uganda, this trend is reflective of the broader SSA context, with limited uptake of CRA technologies often attributed to insufficient support for scaling innovations, constrained access to resources, and inadequate extension services (Kyomugisha, 2018; Kirungi et al., 2023). The adoption rate is further influenced by the proportion of arable and cultivable land, with Africa predicted to have some of the highest potential for arable and permanent crop production globally (Campbell and Thornton, 2014). In Uganda, the adoption of CRA technologies is complicated by limited access to credit, inadequate extension services, the labor-intensive nature of certain technologies, and complexities within the land tenure system. Additionally, some technologies, such as agroforestry, require a significant amount of time to demonstrate tangible benefits, further discouraging widespread adoption (Kyomugisha, 2018).

Other factors that contributed to poor adoption of CRA technologies in Uganda include; cultural beliefs, insufficient promotion and support from the national government, and inadequate infrastructure, such as poor road networks and limited access to reliable markets. These factors collectively hinder the effective dissemination and uptake of agricultural technologies (N'dakpaze, 2022). Also, the variable rainfall, high costs, and limited technical support have been identified as major obstacles to the successful adoption of CRA technologies in Uganda (Mfitumukiza et al., 2020). These barriers highlight the need for targeted strategies to enhance adoption and maximize Uganda's agricultural potential in the face of climate change

Table 6: Continental estimates for adoption of CRA Technological Innovations

Regions	Permanent crops (Million ha)	Agricultural insurance (%of GDP)	Weather index Insurance (Adoption rate)	Soil/water tech adoption	Adoption rates-improved varieties
Regions					
USA and		-	-	-	-
Canada	242.5	0.08	-	-	-
Africa	219.6	6.00	-	-	-
North America	175.25	0.37	-	-	-
Latin America	546.15	0.47	-	-	-
Asia	305.45	1.00	-	-	-
Europe	158.53	-	-	-	-
Oceania	-	0.70	-	-	-
Australia and	-	-	-	-	-
NZ	-	-	>35% crop area	-	-
Mexico	-	-	8% farmers	16%	-
India	-	-	covered	-	-
Kenya	-	-	<1%	<<1%1%	-
Uganda	-	-	3% Small holders	23%(FB)	-
Uganda	-	-	-	23%(F)1%(I	61
Zimbabwe	-	-	-	SFM)	-
Nigeria	-	-	-	8%	-
Malawi	-	-	-	1%	75
Tanzania	-	-	-	-	19
Burkina Faso		-	-	-	20
Benin		-	-	-	40
Guinea		-	-	-	89
Gambia		-	-	-	38
Ghana		-	-	-	95
Mali		-	-	-	50
Senegal		-	-	-	4(NR),52(M)
Togo		-	-	-	44
Côte d'Ivoire			-	-	
Cameroon					

Note: M=new maize varieties, ISF=integrated soil fertility innovations;

Barriers to effective adoption of ST&I based CRA technologies in Uganda

The review findings revealed low rate of adoption for the CRA technologies across the world, though these continue to vary from region to region (Viswanathan et al., 2020; Bajracharya et al., 2023; Ogisi and Begho, 2023). Several barriers have been highlighted by several studies on why adoption of CRA approaches is not successful across the world and different options and recommendations given to rectify the trends.

Table 7: Summary of Technological Innovations for CRA

Barriers to adoption	Study region	References
Limited climate information	Ethiopia	Wakweya, 2023
Socio-economic factors	Nepal	Bajracharya et al.,
Limited advisory services	Ethiopia	(2023)
Lack of asset ownership	Africa	Wakweya, 2023
Political commitment	Africa	
Technical knowledge to apply CRA	Global focus	
Institutional, policy and structural	Sub-Saharan Africa	Campbell and Thornton
factors	Global focus	2014
Limited trust in some technologies		Ogisi and Begho, 2023
Poor access to credit, subsidies and	Sub-Saharan Africa/Uganda	HLPE, (2019)
electricity		Jena et al., (2023).
Technological barriers		Managa et al., 2023

Also, gender-based barriers in agriculture impact the adoption of CSAPs in SSA, placing women at a disadvantage. The review concludes that it is crucial to address the barriers and leverage the drivers to improve the adoption rates of CSAPs in SSA (Ogisi and Begho, 2023). Another setback to climate adoption is linked to limited climate information which hinders farmers from building resilience plans for livelihoods in addition to other leveraging factors such as socio-economic factors such as age, education level, land ownership, contribution of farm income to overall household (Bajracharya et al., 2023). According to Managa et al., 2023; technological barriers have significantly contributed to low adoption of CRA innovations in Uganda and sub-Saharan Africa in general. Such barriers mainly include; limited access to climate information, inadequate irrigation systems, and inadequate use of precision agriculture techniques. The lack of appropriate technologies suitable for smallholder farmers is also a huge setback, since these farmers have limited skills and knowledge in application of technologies in addition to lack of financial resources.

Mechanisms for adoption of ST&I-based solutions for CRA in Uganda

Food insecurity in Uganda remains a significant and growing challenge, worsened by the effects of climate variability. Fifteen years ago, over 89% of Ugandans were considered food secure according to United Nations assessments (FAO, Parelli, & Branca, 2023; Owasa & Fall, 2024), but the situation has since deteriorated. A combination of factors such as increasing population density, unplanned settlement patterns, natural disasters like landslides, and rising rural land conflicts has significantly exacerbated food security issues. These challenges, along with limited arable land, widespread unemployment, hunger, and inadequate access to productive resources, have left the country vulnerable to severe food insecurity (Brenya & Zhu, 2023). Uganda's vulnerability to climate change is further compounded by low levels of public awareness, insufficient mitigation strategies, limited research initiatives, weak analytical capacity, and underfunded institutions (Twinomuhangi et al., 2023; Mwenje & Kumar, 2024).

The country's highly variable climate, characterized by unpredictable rainfall patterns and an increasing frequency of extreme weather events, is expected to worsen, placing agricultural productivity and rural livelihoods at increased risk (Nyasimi et al., 2016; Oriangi et al., 2024). To address these interconnected challenges, a comprehensive, inclusive approach is needed. Recent studies highlight the importance of adopting diverse climate-resilient agriculture (CRA) strategies, which include establishing robust feedback mechanisms, enhancing collaboration among stakeholders, prioritizing extensive training programs, and ensuring the active involvement of local communities in decision-making processes regarding CRA. Technological innovations such as wastewater recycling, advanced water management systems, and the promotion of flood-resistant crops are crucial for strengthening agricultural resilience. In addition, targeted communication efforts to raise awareness and facilitate the adoption of CRA practices are essential.

Programs like Uganda's Crop Intensification Program serve as examples of efforts to improve agricultural resilience by boosting productivity and reducing greenhouse gas emissions (Clay & Zimmerer, 2020). To maximize the effectiveness of these programs, policies should focus on adaptive governance that improves decision-making related to smallholder land use, supports agroecological intensification, and fosters participatory approaches to address social-ecological inequalities (Clay & Zimmerer, 2020). On a global scale, CRA practices emphasize the effective management of key resources such as land, water, cropping systems, and livelihoods (Viswanathan et al., 2020). In Uganda, adopting these practices in a manner that is tailored to the country's unique challenges requires strengthening institutional capacity, fostering sustainable innovations, and ensuring inclusive approaches that specifically address the agricultural sector's needs.

Science, technology, and innovation (ST&I) play a pivotal role in advancing food security and agricultural resilience in Uganda. Strengthening partnerships with rural producer organizations, developing locally adapted genetic materials for challenging conditions, and supporting low-cost, innovative investments are essential steps. Furthermore, ST&I-driven approaches should diversify production systems and enhance value addition at the smallholder level, thereby empowering farmers to sustainably increase productivity and resilience. One of the main challenges to the adoption of climate-smart agricultural (CSA) practices is the uncertainty many farmers feel about the benefits of these technologies (Jena et al., 2023). Several factors, including social, environmental, economic, and institutional barriers, contribute to the slow uptake of these technologies (Ogisi & Begho, 2023). To overcome these barriers, Uganda must invest in agricultural research and development at global, regional, national, and local levels. Strengthening extension services to improve knowledge transfer and empower farmers is critical. Additionally, providing financial support for necessary infrastructure, subsidies, and agroecological systems should be prioritized.

Accelerating the adoption of ST&I-based solutions for CRA requires a focus on several key mechanisms. Strengthening partnerships with rural producer organizations can facilitate the sharing of knowledge, resources, and technologies, creating a support network for smallholder farmers. Developing locally adapted genetic materials for challenging conditions, particularly through research and development, is a crucial step toward reducing dependence on external agricultural inputs. Promoting low-cost, innovative investments is equally important to ensure that smallholder farmers can increase productivity without placing additional financial burdens on their households. Diversifying production systems, including integrating crop and livestock production, agroforestry, and climate-resilient farming practices, is also essential in enhancing farmers' ability to adapt to climate variability.

Improving value addition at the smallholder level by providing farmers with the training and resources to process and market their produce can significantly increase their income and reduce their reliance on raw crop sales, improving overall economic resilience. Strengthening extension services to enhance knowledge transfer and providing subsidies for CSA technologies will empower farmers to proactively adopt these technologies, helping to address the uncertainty many farmers have about their potential benefits. These strategic actions can help to improve food security, alleviate poverty, optimize resource use, and enhance the resilience of Uganda's agricultural systems in the face of growing climate change impacts. Strengthening ST&I-based solutions for CRA enhances sustainable development, improves agricultural productivity, and guarantees the protection of local livelihoods especially to the Uganda's rural population.

CONCLUSION

The study concludes that Africa showcases a range of technical and indigenous CRA innovations, but Uganda lacks comprehensive documentation, with only limited technologies and practices highlighted. While previous studies have targeted resilience, adaptation, and mitigation of climate change impacts, there is a pressing need for ST&I-driven CRA approaches to address food security and nutrition effectively. This requires systematic documentation and evaluation of CRA innovations in Uganda. This lack of systematic knowledge hinders the effective deployment of CRA solutions tailored to local farmers' needs. The study emphasizes enhancing smallholder farmers' capacity to mitigate climate change impacts through targeted initiatives that align with their specific needs. Structural, institutional policy, and scientific measures must prioritize the adoption and diffusion of CRA technologies. Strengthening innovative food systems demands increased public investment in high-quality research and advisory services tailored to agro-ecological production systems. Further, addressing food security and nutrition challenges requires robust, ST&I-driven solutions.

The ST&I-driven CRA approaches offer a transformative pathway to strengthen resilience, adaptation, and mitigation efforts. Addressing institutional failures and the lack of robust policy frameworks is critical for implementing ST&I-based solutions, that will support food availability, accessibility, and adequate quality. The study calls for prioritizing key policy considerations and strengthening scientific and social mechanisms to accelerate CRA adoption for improved food security and nutrition in Uganda and elsewhere. These measures are essential for linking science and technology with food security, advancing agricultural innovation systems, and supporting broader agriculture-led development strategies for climate resilience and sustainable livelihoods.

By integrating scientific research, technological advancements, and innovative practices into agro-ecological production systems, these approaches empower smallholder farmers to adapt to climate variability, enhance productivity, and secure sustainable livelihoods. Public investment in high-quality research and tailored advisory services is crucial to accelerate the adoption and diffusion of CRA technologies; while ensuring they address the unique needs of smallholder farmers—who form the backbone of Uganda's agriculture sector—is a key priority. To maximize the potential of ST&I in CRA, structural, institutional and policy reforms must address existing knowledge gaps on the performance of existing CRA ST&I driven technologies on food security, resilience, adaptation and nutrition in Uganda.

Robust policy frameworks and strengthened Institutional mechanisms should be guaranteed to create enabling environments for CRA innovation. Furthermore, prioritizing partnerships among governments, research institutions, and local communities fosters inclusive and scalable solutions that link ST&I with sustainable food systems and climate adaptation. It is thus necessary to align CRA with ST&I-based solutions, in order to enhance food security, improve nutrition, and build resilient agricultural systems in Africa, and Uganda in particular. This nexus not only drives agricultural innovation but also underpins broader agriculture-led strategies for sustainable development, climate resilience, and economic growth. Recognizing and operationalizing the interconnection between CRA and ST&I is fundamental to building sustainable food systems that not only respond to climate challenges but also drive long-term food security and improved nutrition.

Finally, the study highlights the critical role of science, technology, and innovation (ST&I) in advancing climate-resilient agriculture (CRA) to significantly improve food security and nutrition in Africa, particularly in Uganda. While Africa exhibits a rich diversity of technical and indigenous CRA innovations, Uganda faces a notable gap in the comprehensive documentation and evaluation of these practices. Bridging this gap is essential to leverage CRA innovations effectively in addressing climate change impacts, enhancing food security, nutrition and sustainable livelihoods.

RECOMMENDATIONS

The study highlights the need for deliberate efforts to accelerate the adoption and diffusion of climate-resilient agricultural (CRA) innovations across Uganda and Africa. Central to this effort is increased public investment in high-quality research and development, particularly in areas aligned with agro-ecological production systems that meet the specific needs of smallholder farmers. Investments should prioritize generating research outputs, comprehensive documentation, and robust advisory extension services to ensure effective knowledge transfer and technology dissemination. The study also recommends that deliberate efforts should be made to enhance the adoption and diffusion of CRA ST&I-based innovations in order to increase and strengthen food security and nutrition benefits, as well as livelihood opportunities. To empower small-holder farmers, capacity building initiatives should be at the forefront. Training programs should equip farmers with the technical knowledge and skills needed to implement CRA practices effectively. Moreover, programs should include gender-sensitive approaches to ensure equitable access and participation for women, who play a critical role in agriculture.

Infrastructure development is another critical focus area, including the establishment of improved transportation networks, storage facilities, and irrigation systems to support CRA adoption and enhance market access for smallholder farmers. Additionally, awareness campaigns and feedback mechanisms are essential to build understanding and trust in CRA innovations. Community engagement should be central to decision-making processes, ensuring that the unique needs and challenges of local farmers are adequately addressed. Additionally, policy frameworks should be strengthened to address institutional gaps and provide clear guidelines for the implementation of CRA innovations. Governments and development partners should create enabling environments by fostering partnerships among research institutional, local communities, and private stakeholders to facilitate the development and dissemination of CRA technologies. Strengthening policy frameworks is equally crucial to address institutional gaps and provide clear, actionable guidelines for implementing CRA innovations.

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CONFLICT OF INTEREST STATEMENT

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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