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CAADP XP4 PROGRAMME

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Introduction

The agricultural sector is a key driver of economic growth and one of the most vulnerable to climate change. Recognizing this challenge, global leaders, scientists, social movements, and youth and gender groups have embraced the Climate-Smart Agriculture (CSA) framework as a strategic approach to mitigate climate change impacts on agriculture. Over the years, CSA has gained significant traction across Africa, with widespread adoption by policymakers, researchers, and agricultural stakeholders.

In response to the growing need for coordinated action, the Forum for Agricultural Research in Africa (FARA), in partnership with CCARDESA, CORAF, ASARECA, AFAAS, DeSIRA-LIFT, and other key organizations, convened the 3rd Biennial Africa Climate-Smart Agriculture Stakeholders Conference as part of the Science and Partnership for Agriculture Conference.

The central theme of the conference focused on " Partnerships for food system transition under climate change, soil health, and the biodiversity crisis" Specific objectives included (i) taking stock of progress on major themes in food and agriculture, (ii) sharing lessons using a partnership lens, and (iii) agree on critical collective actions required to steer the continent towards achieving its food and agriculture development targets.

The conference highlighted four major thematic areas of focus;

i. Agroecology, Biodiversity, and Soil Health – Enhancing ecosystem resilience and sustainable farming practices.
ii. Digitalization, Artificial Intelligence, and Precision Agriculture – Leveraging technology for climate adaptation and mitigation.
iii. Youth Engagement, Women Empowerment, and Agribusiness Development – Strengthening inclusivity and economic opportunities in CSA.
iv. Governance and Food System Transition – Addressing policy gaps and promoting sustainable agricultural governance.

Participation & Program Highlights

Held from July 29th 31st, 2024, the conference attracted over 300 stakeholders from across Africa and beyond. The event featured: Opening remarks by key agricultural leaders. Lead paper presentations and discussions on CSA innovations. Three commissioned studies examining CSA progress and future directions. Breakout sessions for in-depth discussions on the four thematic areas.

This conference reaffirmed Africa's commitment to advancing CSA and ensuring that agriculture remains resilient, productive, and inclusive in the face of climate change.

Lead Paper

Ensuring the delivery of the desired future of food systems in Africa

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Abstract

This paper examines the pathways to ensuring the delivery of the desired future of food systems in Africa within the landscape of food systems and food systems transformation. This is predicated on the fact that the triple burden of climate change, population and demand for healthy diets have stressed the need for ensuring the delivery of the desired future of food systems in Africa because global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity. This paper examined different lines of thoughts and argument and synthesized a common position for Africa through prescriptive and advisory activities that should be efficiently combined in implementation not in a mutually exclusive nor exhaustive version which includes linking agriculture and nutrition through nutrition-sensitive interventions or programs which addresses the underlying determinants of food and nutrition security as well as development, improving the health and resilience of Africa's soil in all agricultural sub-sectors for the simultaneous benefits of increasing agricultural productivity, reducing the prevalence and degree of fragmentation and competition among actors based on proof of concept, and diversification of agriculture such that there transformation from reliance on only 30 plant species that are responsible for producing nearly 95% of the food globally. Others are eliminating the divergence rather than congruence in activities, finance and application among these subsystems should be brokered to remove multiplicity and duplication of role players and activities with limited impacts, improving the processes by which the agriculture role players and service providers are held accountable to the people at lower levels, maximizing the benefits of technology/innovation through scaling, and digitization of value-chains for the effective transformation of food systems for effective coordination, harmonization and regulatory services.

Keywords: Food systems, food systems transformation, future of food, sustainable food system

Introduction

Ensuring food security has become an issue of key importance to countries with different degrees of economic development, and the agricultural sector plays a strategic role in improving the availability of food, having a much greater impact on reducing poverty and improving food security than the other sectors of the economy (Gates Letter 2015). Agriculture is central to food system transformation and its contributions to several Sustainable Development Goals (SDGs) such that the issues related to food and agriculture are expansively integrated among the seventeen Sustainable Development Goals (SDGs) and 169 targets (FAO, 2024). The goals on end poverty includes targets related to social protection, land rights and resilience, while SDG2 is dedicated to ending hunger, improving food security and nutrition, and promoting sustainable agriculture. The link between food security and natural resources features prominently in SDG14, oceans and marine resources, SDG15, ecosystems, biodiversity, forests and land, as well as SDGs on water, energy, gender, climate, and consumption and production (FAO, 2024). The link between climate change and nature manifesting in terms of loss of biodiversity, damaged infrastructure, loss of crops, land degradation, drought, loss of species, disrupted seasons, and broken agro-diversity as well as the connection between climate change and society expressed in food insecurity, water scarcity, outbreak of diseases, social equity, poverty & displacement, economic instability, loss of livelihoods and broken food system have led to the overall implications of ballooning cost of health impacts on food systems and dietary risks accounting for the highest number of deaths.

The triple burden of climate change, population and demand for healthy diets have stressed the need for ensuring the delivery of the desired future of food systems in Africa. The efforts to ensure food and nutrition security is demanding more interventions to sustainably increase agricultural production, improve the global supply chain, decrease food losses and waste, and ensure access to nutritious food. To achieve these objectives sustainable agricultural practices and food systems, from production and consumption perspectives, must be pursued from a holistic and integrated perspective. The expected changes in temperatures, precipitation and pests associated with climate change, the global community is called upon to increase investment in research, development and demonstration of technologies to improve the sustainability of food systems everywhere. The building of resilience of local food systems will be critical to averting large-scale future shortages and to ensuring for all food security and good nutrition (United Nations, 2024).

The Africa continent is on race against time in meeting the SDG goals with 2030 as the target date particularly goal 13 on climate actions as many of the indicators for this goal are not on track. According to United Nations Statistics Division (UNSD) (2023), a midpoint evaluation of SDG progress on the journey to 2030 reveals significant challenges, and the global-level data and custodian agencies analysis show that among the assessable targets, a meagre 15 per cent are on track to be achieved by 2030; while 48 per cent of the targets assessed show deviations from the desired trajectory. Similarly, 37 per cent of the targets recorded no progress or regressed below the 2015 baseline. This comprehensive assessment underscores the urgent need for intensified efforts to ensure the Sustainable Development Goals stay on course (United Nations Statistics Division (UNSD) 2023). Many of the Sustainable Development Goals (SDGs) remain unattained due to the current food systems failing to end malnourishment but also exhibit substantial ecological impacts. The costs of poor nutrition, including economic, health and environmental impacts, are double the cost of global food consumption.

Nutrition as outcome of agricultural intervention

When nutrition is considered as the outcome of agricultural interventions, the prevalence of undernourishment remain high as underlined by trade policy aimed at enhancing trade openness; boosting food production through innovative technologies; maximizing agricultural land use; adaptation and adoption of farming techniques; investment in agricultural infrastructure; improvement in irrigation infrastructure; investment in agricultural research to improve crop yields; offering services for agriculture; improvement in extension services and training programs for farmers; technical and administrative support for farmers; policies aimed at increasing the households' purchasing power (Pawlak, & Kołodziejczak, 2020). Krishna-Bahadur et al (2018) asserted that the global agricultural system currently overproduces grains, fats, and sugars while production of fruits and vegetables and protein is not sufficient to meet the nutritional needs of the current population and that the only way to eat a nutritionally balanced diet, save land and reduce greenhouse gas emissions is to consume and produce more fruits and vegetables as well as transition to diets higher in plant-based protein. Such a move will help protect habitats and help meet the Sustainable Development Goals. The impact of the food system on human health was underscore by the connection between nutrition and human resilience; as obesity and its associated chronic diseases have surpassed hunger as the leading cause of death, with poor diets as one of the highest contributing factors (WHO, 2022). The Global and regional disruptions to food systems have exposed the vulnerabilities of most African countries as African food systems are under pressure from the growing population, the changing climate, low productivity and rapid urbanization. The triple challenge to food systems requires a transformation where production and trade systems recognize the inherent challenges of African agriculture. High-external inputs, resource-intensive production systems have resulted in massive deforestation, water scarcity, biodiversity loss, soil depletion and high levels of greenhouse gas emissions.

Sustainable food system

A sustainable food system should embody the full food supply chain relative to human consumption, from agricultural activities and other production practices, through to handling, transportation, storage, processing, distribution, consumption, waste management, and recycling/disposal. Similarly, achieving sustainable food systems requires a multi-stakeholder approach, where all parties agree on pathways towards sustaining production while maintaining the natural balance and guaranteeing present and future generations a livelihood. Closely, related to the concept of sustainable food system is the concept of agrodiversity. This is based on the fact that diversified agro ecological systems have proven to be more resilient to the changing global climatic conditions (Leippert et al., 2020); thus, agroecology can attain 'triple wins' to guarantee sustainable food systems, in agriculture through increased agricultural productivity while contributing to the community and agro ecosystems resilience. This promotes the production of targeted nutrition-rich crops, homestead gardens, and diversification of the agricultural production system towards fruits and vegetables and aquaculture can potentially improve nutrient intake and nutritional outcomes. According to Pandey et al (2016), the multiple pathways through which agriculture can influence the nutritional outcomes include source of food, source of income of households engaged in agriculture, for food and non-food expenses, agricultural policy and food prices, women in agriculture and their socio-economic status, maternal employment in agriculture, child care and feeding, and women in agriculture, maternal nutrition, and health status.

Mismatch between food produced globally, and requirements for healthy & balanced diets

The sustainable food system needs agricultural development to proceed in a way that maximizes opportunities to improve health and nutrition and to limit environmental damage in order not to transgress the planetary boundaries while providing a nutritious diet to a growing world population by reversing the mismatch between food produced globally, and requirements for healthy & balanced diets (Chen et al 2019). An analysis of production and consumption using Harvard's Healthy Eating Plate stated that consumption should reflect mostly vegetables, fruit, and whole grains, healthy fats, and healthy proteins, drinking water instead of sugary beverages, and common dietary items such as salt and sodium, vitamins, and alcohol (Chung 2012). According to Ruben et al (2021, several paradigm shifts are necessary for food transformation to enhance the integrated performances of food systems to respond to current and future policy challenges. The system perspective of food transformation harnesses the different ideas, language and concepts in terms of food system outcomes, transformation, transition pathways, resilience, equity, trade-offs and synergies, living income, nature positive approaches, agroecology and the true cost of food. The concepts on power structures, the political economy, stakeholder engagement and dialogue, empowering excluded voices, market externalities, coalitions, economic incentives, and data needs were also covered. Van Bers et al. (2019) define food systems as involving 'complex networks of actors, activities, and flows that the demand system approaches'.

The future of food and its production within the circular bio-economy

The future of food is dependent on complex issues related to sustainable food production, food security, climate-resilient and digitalized food supply chain, alternative protein sources, food processing, and food technology, the impact of biotechnology, cultural diversity and culinary trends, consumer health and personalized nutrition, and food production within the circular bio-economy. Similarly, Galanakis (2024) stated that the future of food relies on innovative approaches that balance nutrition, health, technology and environmental responsibility. FAO (2024) through the Corporate Strategic Foresight Exercise identified triggers of change for the future of food namely institutions and governance; consumer awareness; income and wealth distribution; and innovative technologies.

The transition of the current linear development model to a circular bio-economy approach can enhance resilience by providing opportunities to embrace food waste and other biomass substrates, as circularity enhances recycling and reusing resources in a way that circularity and sustainability "emphasis intra- and intergenerational commitments motivated by environmental hazards and signal the importance of increasing agency and public deliberation upon the multiple and coexisting pathways for development." UN (2024) stated that about a-third of all human-caused greenhouse gas emissions are linked to food and thus food needs to be grown and processed, transported, distributed, prepared, consumed, and waste disposed. Food production from agricultural process and land use are closely related to methane emission from cattle's manure enteric fermentation, nitrous oxide from fertilizers used for crop production, carbon dioxide from forests exploitation for farmland expansion, and other agricultural emissions from manure management, rice cultivation, burning of crop residues, and the use of fuel on farms. Similarly, greenhouse gas emissions related to food value-chain are linked to refrigeration and transport of food, industrial processes such as the production of paper and aluminum for packaging, and food waste management. The figure on the kilograms of greenhouse gas emissions per kilogram of food depicts that animal-based foods, are generally associated with the highest greenhouse gas emissions, while plant-based have lower greenhouse gas intensities, thus the implications for the carbon footprint in terms of nutritional units (per 100 grams of protein or per 1000 kilocalories) and efficient use of different foods supply protein or energy are revealed (Babiker et al 2022, Poore and Nemecek 2018).

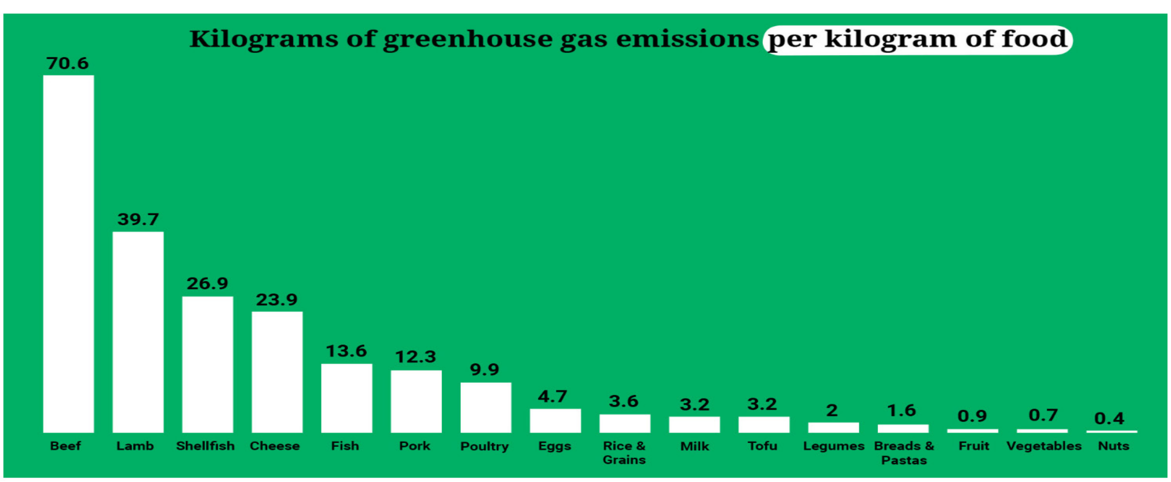

Figure 1: Kilograms of greenhouse gas emissions per kilogram of food
Source: UN (2024) Food and Climate Change: Healthy diets for a healthier planet.

From the foregoing, this paper posits that to ensure the delivery of the desired future of food systems in Africa the following prescriptive and advisory activities should be efficiently combined in implementation not in a mutually exclusive nor exhaustive version. The approaches for the future of food should enhance that improved delivery paths are sought and transformation of the scaling of proven methods in the implementation processes.

Nutrition sensitive agriculture - A major approach to ensure the delivery of the desired future of food system in Africa is the targeting of nutrition outcomes of agricultural intervention. A major approach to linking agriculture and nutrition is nutrition-sensitive interventions or programs which address the underlying determinants of food and nutrition security as well as development; including caregiving resources, health services, safety and hygienic at the household and community levels within their production system as reflected in the farming system. Dixon *et al* (2012) noted that farming systems practiced influenced level of undernourishment as widespread and severe household food insecurity occurs in many farming systems and food insecurity and poverty are interrelated. There are linkages between agriculture and nutrition such that the national nutritional profile influences national economic growth because a key outcome of agricultural activities is food and a key input into proper nutrition. Similarly, agriculture is associated with many of the world's major health problems, including undernutrition, malaria, HIV/AIDS, foodborne diseases, diet-related chronic diseases, and a range of occupational health hazards, thus agriculture, contributes to both the spread and alleviation of these health conditions (Hawkes & Ruel, 2006).

The Soil Initiative for Africa (SIA) - A major potential for enhancing the food and nutrition security in Africa is the availability of more than 65% of arable lands within the continent, which however has been marked by low fertility, poor nutrients and low productivity. The soil as the foundation for improved food and nutrition security as well as the critical resource in the source and sinks of soil carbon for adaptation and mitigation of climate change effects. According to FARA (2024) "The Soil Initiative for Africa (SIA) provides a long-term framework to guide investments and efforts to improve the health and resilience of Africa's soil in all agricultural sub-sectors for the simultaneous benefits of increasing agricultural productivity, improving water availability, increasing agricultural resilience to the effects of climate change and other shocks, turning smallholder and emerging farming systems into profitable rural businesses for sustained livelihoods, supporting commercial farming systems to practice sustainable soil management and contribute their knowledge through technology transfer. Founded in the AU vision of "an integrated, prosperous and peaceful Africa, driven by its own citizens and representing a dynamic force in the international arena", the SIA Framework puts particular emphasis on the importance of Africa's farmers and communities as champions of change and agents of Africa's agricultural transformation in alignment with national priorities".

African Agricultural Research, Innovation and Education Institutions (AARIEIs) - To ensure the delivery of the desired future of food system in Africa, there is need for more synergy among Agricultural Research, Innovation and Education Institutions. The degree of fragmentation among actors along the geographical and thematic line reveals more than 50 national research systems, most of which are small, with limited capacity and a mandate covering diverse agricultural ecologies. Similarly, research, extension, education, private sector, producers, policy working in silos have contributed to limited impact of research. The landscape therefore boasts of competition rather than subsidiarity and effective linkages. The African Agricultural Research, Innovation and Education Institutions AARIEIs would help in Developing stronger synergies and organic relationships within AARIEIs by affirming development of stronger synergies and organic relationships within AARIEIS, partnership among AARIEIs to ride on, borrow from existing arrangements and constructed based on lessons and experiences from existing consortia and partnership; based on existing proof of concept demonstrating the potential for successful collaboration and impactful outcomes in order for effective coordination, harmonization and regulatory services.

Vision for Adapted Crops and Soils (VACS) - A major response to the current diets in most countries that are neither healthy nor environmentally sustainable (Springmann et al 2020) are the use of orphan, neglected, underutilized, future crops as variously depicted. Orphan crops are recognized as nutrient-rich crops, together with their wild crop relatives, contribute to more than 90% of the global diet, bring diversity in agriculture and serve as resource material for agricultural research to further increase the stress-tolerance of major food crops; have high-level adaptation to heterogeneous and harsh agro-ecological conditions, that enhance regenerative and ecological processes but are often depicted as "poor peoples' crops," that improve their food and nutrition security and income-generating opportunities (Azam-Ali et al., 2021). There are needs therefore for diversification of agriculture such that the transformation from reliance on only 30 plant species that are responsible for producing nearly 95% of the food globally leading to reduced diversity among the major crops, and biodiversity getting drastically reduced to the inclusion of orphan crops (Shelef et al. 2017). The orphan crops also serve as genetic resource for crop improvement through the identification of genes or signaling mechanisms responsible for stress tolerance can be a big boost in our efforts to improve the stress tolerance of major crops. Kumar and Bhalothia (2020), and Nowak et al. (2016) noted that the diversity in the human diet is enhancing the shifting of food habits and lifestyle towards healthier food options as orphan crops are rich in many secondary metabolites with antioxidant properties that are beneficial for the human body preventing diet-related pandemics.

Brokering solutions linking finance, research, and extension - A main method ensure the delivery of the desired future of food system in Africa is the elimination of the gaps in the science of discovery and science of delivery as well as the art of finance among the International Financial Institutions, Multi-lateral Development Banks, agricultural research, consultative group of international agricultural research and ministries/ departments within agriculture sector by brokering solutions linking IFIs, MDB with Research, CGIAR, actors, Ministries. The divergence rather than congruence in activities, finance and application among these subsystems should be brokered to remove multiplicity and duplication of role players and activities with limited impacts.

Downward accountability - To ensure the delivery of the desired future of food systems in Africa, there is need for more downward accountability among role players in the agriculture landscape. The role players, namely research, extension and development agencies within the agriculture landscape, have been more upward accountability than downward accountability. The upward accountability in which the organization is accountable up the organizational chain to board or donors, which depicts the traditional principal-agent relationship, where donors use various compensation contracts and monitoring systems to hold those below them in the organizational to account. The downward accountability refers to processes by which the agriculture role players are held accountable to the people at lower levels; such that downward accountability relates to the ability of those being served evaluating the actions of service providers; demanding answers; and based on the evaluations, imposing sanctions or rewards. Nettle et. al.2017; Kabir, et al 2020, Mbeche, et al 2022 stated that the key indicators of downward accountability in an agricultural system are (1) participation of farmers in decision-making, (2) farmer empowerment, (3) responsiveness of extension to the needs of farmers, (4) interaction and participatory dialogue, (5) decentralised delivery of extension services, (6) inequality in the power structure, (7) sustainability, (8) financing, (9) inclusivity and (10) private sector coordination and regulation.

Scaling - To ensure the delivery of the desired future of food systems in Africa, there is need for the maximization of the benefits of technology/innovation which is often depicted as scaling. The fact that scaling has become a popular concept and attracting the interest of many agencies notwithstanding, the science and practice of scaling remain at early development stages (Gebreyes et al., 2021). Scaling consists of a continuous process in which innovations are tailored, used, and embedded into societal dynamics adapted to various contexts, aiming to create widespread positive impacts, which can be (1) by adapting knowledge and innovations to the conditions of different end-users, which requires understanding the principles underlying an innovation (horizontal scaling); (2)benefits to more people over a wider geographic area more quickly, more equitably, and more lastingly (scaling up); (3) localizing high-level strategies and a form of devolution in which higher level actors engage local actors in order to get sufficient space and support to implement their intended action (scaling down); (4) actions taken by individuals and social groups to challenge and undermine existing arrangements which tie particular decision-making to certain scales (scale bending); and (5) reframing local issues in terms of regional, national or even global interests which is important when there are critical constraints such as finance, capacity and political legitimacy at the local level, which can only be resolved through resource mobilization or advocacy at higher decision-making levels (scale jumping).

Digital Agriculture - Digitalization is another major approach to ensure the delivery of the desired future of food systems in Africa. AgriTech solutions are globally distributed and cover advisory & information, market linkages & access, financial access, supply chain management, enterprise management & efficiency, and enterprise research & development, with the largest proportion from sub-Saharan Africa (50%), 21% from South Asia (21%) and 18% Latin America and the Caribbean. Similarly, the cumulative annual growth rate of the number of ICT4Ag solutions from 2012 to 2018 (33% per annum) was more than three times larger than that for the next four years, from 2018 to 2022 (9% per annum); and AgriTech Innovation is decentralizing with "61% of solutions in Latin America and the Caribbean, 86% in South Asia, and 45% in sub-Saharan Africa from Kenya and Nigeria. ICT4Ag Reach is soaring with more than 50 million active users accounting for 10% of smallholder farming households in Low- and Medium-income countries with the basis that the impact of AgriTech, but there is still more "noise" than "signal" with the "evidence" remains mostly anecdotal and housed in innovators' marketing collateral (Beanstalk AgTech, 2023). All these indicators have implications for the digitization of value-chains for the effective transformation of food systems.

Conclusion

This paper posits that climate change, population and demand for healthy diets have stressed the need for ensuring the delivery of the desired future of food systems in Africa. It examined the interrelatedness of agriculture and sustainable development goals. Nutrition is considered as the outcome of agricultural interventions, the complexities of sustainable food system, paradigm shifts for food transformation, Mismatch between food produced globally, and requirements for healthy& balanced diets, Food Production within the Circular Bioeconomy. The paper further stated that the approaches for the future of food should enhance that improved delivery paths are sought and transformation of the scaling of proven methods in the implementation processes which includes Nutrition sensitive agriculture, The Soil Initiative for Africa (SIA), African Agricultural Research, Innovation and Education Institutions (AARIEIs), Vision for Adapted Crops and Soils (VACS), Brokering Solutions linking IFIs, MDB with Research, CGIAR, actors, Ministries, Downward accountability, Scaling and Digital Agriculture. The efficient combinations of the listed pathways, not in a mutually exclusive nor exhaustive version, would ensure the delivery of the desired future of food systems in Africa.

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Commissioned Study 1

Advancing climate smart actions using Science, Technology and Innovation (STI): Prospects for a sustainable agricultural system in Africa

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Key Messages

Expand Science, Technology, and Innovation (STI): With an additional 230 million people to feed in urban areas by 2030, there is an urgent need to significantly expand science, technology, and innovation in agricultural systems to boost productivity, ensure food security, and build climate resilience.

Improve Enabling Policies and Governance: It is essential to greatly improve policies and governance frameworks to facilitate access to and use of climate finance. Strengthening these systems will enable countries to implement effective climate adaptation and mitigation strategies in agriculture.

Foster Private Sector Investment: Embracing private sector approaches is critical to unlocking much greater levels of investment in science and technology within food systems. Partnerships between governments, private enterprises, and research institutions can drive innovation and improve sustainability.

Increase Research and Development in STI: There is a pressing need for more research and development in Science, Technology, and Innovation to address the evolving challenges of climate change in agriculture. Investments in R&D will enable the creation of solutions tailored to local contexts and future climate risks.

Introduction

Global economic imbalances, soaring population growth and the impact of climate change need to be overcome to enhance the sustainable process of economic development (Divergencies, 2023). Agriculture contributes significantly to the socioeconomic landscape of Africa. Crop and livestock production is diverse, and most African economies rely on rain-fed agriculture which is very sensitive to climate change and variability (Omotoso, 2023). More than 45% of total crop production value in the continent comes from five main crops including maize, rice, potatoes, cassava, and a combination of fruits and vegetables. Livestock production also contributes more than a third of Africa's agriculture GDP by providing livelihood income, food, hide and in some cases manure for crop production.

The African Development Bank estimates that the agricultural and food market scale of the African economy could grow to a market value of US$ 1 trillion in 2030, from US$280 billion a year in 2023 (Ogiogio, 2022). It further highlights that the market value could triple if innovative solutions and policies consider the impact of climate change, support systems for agriculture, farmers, and agribusinesses. However, McLymont (2014) reports that the continent spends an estimated US$78 billion annually on food imports whilst utilizing only 6% of its land for permanent crops. Crop pests annually account for account for up to 40% of African food losses translating to over US$200 billion losses annually.

Global warming is further having significant adverse effects on agriculture in Africa. Extreme climatic events such as floods and droughts are both devastating to the agriculture sector. Droughts affect food production, water resources and cause widespread human and animal mortalities (Lottering et al., 2020). Floods, as well, directly destroy productive assets, such as livestock and crops, and indirectly by engendering income loss from not being able to liquidate lost assets (Balgah et al., 2023). Climate extreme events further entrench food insecurity in sub-Saharan Africa and places about 75% of Africans at risk of hunger by 2080 (Ching, 2010). The loss of crop yields will also affect food prices, lead to inflation rise and further push more people into poverty (Kunawotor, 2022).

Already the region suffers from recurring risks to food production, and without adequate measures to adapt, these risks could become more intense under a changing climate. Persistent poverty and socioeconomic inequality, low levels of development, limited economic capacity as well as governance challenges have further contributed to the continent's limited capacity to adapt to climate change. Khan *et. al*, (2021) notes that science, technological and innovative advancement in recent years have played a significant role in improving productivity through digital agriculture, food processing and safety, gene technology, health, agricultural inputs and resource use efficiency.

Climate smart actions also provide an opportunity for the application of innovative solutions and technology in increasing the region's resilience. Climate-smart science, technology, and innovations (STIs) could help reduce the negative impacts of climate change on agriculture. By linking research and innovation with development efforts, agriculture could become more resilient to climate change and better meet the region's development goals. STI support sustainable economic and social progress by introducing technologies that increase productivity, competitiveness, and growth while improving livelihoods (Taruvinga, 2023).

Aside developing new technologies to adapt the agriculture sector to climate impact, African governments development of innovative policies and enabling environment to support and implement these solutions presents a positive way forward (Lybbert and Sumner, 2010). Through Agenda 2063, the African Union aims to modernise agriculture and increase productivity through the application of science, technology and innovation systems, although investment in science, technology and innovating is observed as very low in Africa (Walsh *et. al.*, 2020).

Understanding the relevance of Science, Technology, and Innovation (STI) is crucial for safeguarding agriculture from the impacts of climate change. By exploring case studies and best practices, we can gain insights into how these tools have been successfully applied to enhance agricultural resilience. Additionally, identifying the challenges faced by farmers and policymakers in adopting STI solutions, as well as future opportunities for innovation, is essential for shaping strategies that support sustainable agricultural development and climate adaptation across Africa.

Current climate smart actions

Climate change has a significant impact on agriculture, such as implementing strategies that reduce carbon emissions and resilient approaches that help agriculture adapt to climate change is imperative and essential for sustainable agricultural development and food security (Lou et al., 2024). Adaptation involves adjusting physical infrastructure to prepare for climate-change related changes in the local environment (Almeida *et al.*, 2024). Climate-smart agriculture (CSA) practices aim for sustainable farming by managing resources efficiently (Sarker & Wu, 2019).The principal goal of CSA is to ensure food security and development and provide an opportunity to respond to the impacts of climate change whilst enhancing the livelihood of farmers.

A study conducted by Maguza-Tembo et al. (2016) found significant increase in maize yield by farmers who adopted CSA strategies such as portfolio diversification, soil and water conservation, soil fertility improvement and irrigation and water harvesting technologies respectively. The results further noted that adopters of the CSA strategies earned about 40% of income revenue compared to non-adopters. Over the years, evidence has demonstrated the impact of CSA on agricultural productivity and farmer livelihoods (Makate, 2019; Dinesh *et al.*, 2018). In addition, the application of integrated soil fertility management practices with cropping systems is highly associated with improved soil nutrient uptake and crop yields (Milcu *et al.*, 2013).

In response to the escalating impacts of climate change on agriculture and food security, African countries are increasingly adopting climate-smart actions. These strategies focus on enhancing agricultural productivity, building resilience to climate-related shocks, and reducing greenhouse gas emissions where possible. Current climate-smart practices include sustainable land management, improved water-use efficiency, the adoption of drought-tolerant crop varieties, and the integration of digital technologies to optimize farming practices (see case studies in Boxes 1 and 2).

Box 1: Case studies of use of climate smart actions in Africa

Case Study 1: Implementing digital technologies to disseminate agricultural best practices

Overview: Improve agricultural productivity and incomes through the use of digital technology.

Impact and Outcomes:

Increased Crop Yields: Farmers who participated in the program reported an increase in crop yields.

Cost Reduction: The use of video technology reduced the cost of agricultural extension services .

Farmer Reach: Over 100,000 smallholder farmers reached with valuable agricultural information.

Lessons Learned:

Effective Knowledge Transfer: Digital tools can effectively transfer knowledge and improve agricultural practices.

Scalability: Digital platforms can be scaled up to reach a large number of farmers with limited resources.

Case study 2: Water Efficient Maize for Africa

Overview: Develop and distribute drought-tolerant and insect-resistant maize varieties.

Impact and Outcomes:

Enhanced Food Security: Adoption of WEMA maize varieties has led to increase in maize yields during drought conditions.

Economic Benefits: Farmers reported increase in income due to higher yields and reduced need for pesticides.

Lessons Learned:

Public-Private Partnerships: Collaboration between public institutions and private companies can drive successful agricultural innovations.

Community Engagement: Involving local farmers in the development and test

Case study 3: Green Growth and Climate Resilience Strategy and African Adaptation Initiative

Overview: Focuses on mainstreaming climate resilience into all sectors of the economy and promoting low-carbon development.

Impact and outcomes:

Guides national development towards sustainability and climate resilience.

AAI Overview: An African-led initiative to enhance the continent's adaptation efforts and mobilize resources for climate resilience.

Strengthens regional cooperation and resource mobilization for adaptation projects.

Box 2: Country specific case studies of use of climate smart actions in Africa

Case study 4: Agroforestry - Trees for the Future in Ghana

Overview: Training farmers to integrate trees into their farming system. Improve soil health, increase biodiversity, and enhance livelihoods through agroforestry.

Impact and Outcomes:

Soil Health: Improved soil fertility and reduced erosion due to the presence of trees.

Biodiversity: Increased biodiversity and habitat for wildlife.

Lessons Learned:

Long-Term Benefits: Agroforestry provides both immediate and long-term benefits to farmers and the environment.

Community Involvement: Engaging communities in planning and implementation is key to the success of agroforestry projects.

Case study 5: Rooftop Rainwater Harvesting in Ethiopia and Drip Irrigation

Overview: Collecting and storing rainwater from rooftops for agricultural and domestic use.

Implementation of low-cost drip irrigation systems for smallholder farmers.

Impact and outcomes:

Provides a reliable water source during dry seasons and reduces pressure on traditional water sources.

Efficient Irrigation Systems

Increases water use efficiency, boosts crop yields, and reduces labor requirements.

Case study 6: Solar Pump Project in Zambia

Overview: Provide affordable and sustainable irrigation solutions to smallholder farmers.

Impact and Outcomes:

Improved Crop Yields: Farmers using solar pumps reported increase in crop yields due to reliable irrigation.

Water Efficiency: Solar pumps use less water compared to traditional irrigation methods.

Income Growth: Participating farmers saw their incomes rise due to increased production and reduced costs.

Lessons Learned:

Sustainability: Renewable energy solutions can significantly reduce operational costs and environmental impact.

Accessibility: Providing affordable financing options is crucial for widespread adoption of new technologies.

Scaling these actions requires more robust investments in science, technology, and innovation, along with stronger policy frameworks and collaborative efforts across the public and private sectors. Studies such as Kombat *et. al.*, (2021) also note that CSA adoption is context and location specific. Subsequently, a combination of CSA technologies are being used more often depending on farmer knowledge, local and climate conditions. According to Matteoli et al. (2020), some of the most widely adopted CSA practices in Africa include conservation agriculture, the cultivation of drought-tolerant crops, the use of wetlands, and integrated crop-livestock farming. Additionally, crop diversification, irrigation, early-maturing crop varieties, integrated soil fertility management, and integrated pest management (see Table 1 below) have been instrumental in improving crop productivity and enhancing the adaptive capacity of farmers to climate-related stresses (Erekalo & Yadda, 2023).

Table 1: Examples of the use of science and technology in agriculture

Issue	Examples of science and technology for food security
Urban agriculture	Aquaponics Low-cost greenhouses
Post harvest losses	Fruit preservation technologies Biowax coating Parboiling technology Refrigeration Solar dryers Agro-processing technologies (crop, meat, dairy products, fish) Crop threshers (motorized and bicycle-powered)
Lack of nutritious food	High-nutrient staple crops Vitamin A-enriched cassava, maize, orange-fleshed sweet potato Iron and zinc-fortified rice, beans, wheat and pearl millet quality
Food stability: Early warning systems & finance	Weather-forecasting technologies Infrared sensors for detecting crop stress Hyperspectral imaging, based on drones and satellites Index-based insurance (crop and livestock)
Biotic & abiotic stresses	Disease - or pest-resistant crops Climate-resistant crops
Crop productivity	Conventional breeding Tissue culture and micropropagation Advanced genetic engineering
Livestock productivity	Low-cost diagnostic toolkits for livestock veterinarians Tissue engineering for laboratory-grown animal products

Water availability	Micro-irrigation technologies, drip irrigation, microsprinkler irrigation Planting technology for increased water efficiency Rainwater harvesting mechanisms Water desalination technologies Wastewater reuse Portable sensors for groundwater detection
Precision agriculture	Drones Internet of things Big data Farm management software and applications Robotic technologies

Relevance of Science, Technology and Innovation (STI) in climate smart actions

Science and technology play a crucial role in scaling and optimizing CSA practices. Advances in biotechnology, for instance, have enabled the development of drought-resistant and pest-resistant crop varieties, while innovations in digital agriculture—such as precision farming, satellite monitoring, and data-driven decision-making tools—are improving water-use efficiency and resource allocation (Bertoglio *et al*. 2021). Furthermore, science-driven approaches to integrated pest management and soil health monitoring have proven essential for sustainable agriculture under changing climate conditions. As well, the advancement of research into the promotion of genetically modified seeds and crops has resulted in the increased studies of innovation as a route or opportunity to food self-sufficiency in Africa (Azadi *et al* 2015, Gbadegesin *et al* 2022). The study asserts that the use of Genetically Modified crops significantly boosts agricultural productivity while decreasing maintenance costs such as pesticides costs. Citing that, farmers cultivating Bt (Bacillus thuringiensis) maize compared to conventional maize, in South Africa, achieved yields ranging from 7% to 12% higher in 1999-2001 (Bothma *et al.* 2010).

Recent integration of big data analytics in climate science and agricultural research has led to the acceleration of improved scenario analysis, leading to accurate information and prediction in agricultural research and innovation for climate-smart agriculture (Rao, 2018). This has resulted in an increased application of advanced technologies in planning and designing policies for accelerated agricultural growth (Girvetz *et al.*, 2017).

Moreover, CSA technologies particularly for medium and large-scale farmers often necessitate the employment of geospatial technologies such as remote sensing, geographic information systems, and autonomous drones among others (Van Loon *et. al.*, 2020). A number of strategies and farm technologies have emerged for the practice of Climate-Smart Agriculture (Rosenstock *et al.*, 2015). Huang et al., (2018) explains that agricultural remote sensing improves productivity by enhancing farm monitoring by improving precision agriculture through real time data. More recently, the use of the internet of things (IoT) and artificial intelligence technologies have resulted in much more efficient farming methods (Subeesh and Mehta, 2021).

Innovative methods used in Europe categorised climate-smart livestock and improved animal husbandry as processes to lower emissions and boost livestock productivity through the use of cow dung and poultry droppings as manure (Adesipo *et al.,* 2020). In Kenya and Tanzania, this innovation evolved into household technology use, with the construction of two biogas digesters to produce renewable energy from cow manure (Nciizah and Wakindiki, 2015). Further to enhance sustainable agriculture and curb the constraint of information asymmetry towards CSA adoption, farmers in Kenya are using ICT devices such as mobile phones, radios, and movies to spread mitigation techniques and increase public knowledge of climate change. This has resulted in the increase of adoption of climate-smart practises including modern irrigation farming (Turyasingura & Chavula, 2022). While in South Africa, the best agricultural techniques for climate-smart agriculture especially for smallholder farmers, were found to include rainwater gathering and early maturing and drought tolerant seeds (Senyolo **et al.**, 2018),.

Science and technology are pivotal in advancing climate actions, particularly in agriculture, by driving innovation, enhancing adaptive capacities, and improving productivity. The Tables 2 below highlights the relevance of science and technology in key climate-smart actions, demonstrating how innovations in areas such as biotechnology, digital agriculture, and resource management are essential for addressing climate challenges and ensuring sustainable development. These advancements not only enhance resilience to climate shocks but also promote more efficient and sustainable use of natural resources. Additionally, Table 3 showcase the importance of technological innovation in driving transformative solutions, from digital agriculture and resource management to energy efficiency and ecosystem protection. These innovations are essential for enabling more effective climate adaptation efforts across various sectors.

Table 2: Relevance of science and technology in climate actions

Science and Technology	**Relevance**
Climate research and data collection:	
- Climate Modeling and Forecasting - Remote Sensing and Satellite Data	Provide accurate predictions of climate trends to guide agricultural planning and decision-making Monitor environmental conditions and changes in real-time
Soil and crop systems management:	
- Drought-Resistant Crops - Soil Fertility Enhancement	Develop crop varieties that can withstand drought conditions an d ensure food security Improve soil health and fertility to boost crop yields sustainably
Animal Science:	
- Breeding Resilient Livestock - Improving Feed Efficiency	Enhance the resilience of livestock to climate stresses such as heat and disease Enhance the efficiency of livestock feed to reduce costs and environmental impact.
Integrating Science in CSA Practices:	
- Participatory Research and Farmer Engagement - Knowledge Transfer and Capacity Building	Involve farmers in the research process to ensure the practical applicability of scientific innovations. Enhance the skills and knowledge of farmers, extension workers, and policymakers

Table 3: Relevance of technological innovation in climate actions

Technological Innovation	**Relevance**
Digital Agriculture:	
- Precision Farming Techniques - Use of Drones and Sensors	Optimize field level management regarding crop farming. Enhance monitoring and management of crops and fields

Biotechnology:	
- Genetically Modified Organisms (GMOs) for Resilience.	Develop crops with improved traits such as drought tolerance, pest resistance, and higher yields
- Bio-fertilizers and Bio-pesticides.	Enhance soil fertility and control pests using environmentally friendly biological agents.
Renewable Energy:	
- Solar Powered Irrigation Systems	Provide reliable and sustainable water supply for irrigation using renewable energy
- Biogas and Biomass Energy Solutions	Utilize agricultural waste to produce clean energy for farming activities and households (biodigesters).
Integrated Technological Systems:	
-ICT Platforms for Climate Information	Provide farmers with timely and relevant climate information to make informed decisions.
- Innovative Financing and Insurance	Provide financial products and services that reduce the risks associated with climate variability.

Key Challenges and enablers in implementing Climate-Smart Science, Technologies and Innovations

Challenges

The United Nations projects that global population will rise to 9.7 billion by 2050, significantly increasing the demand for food (FAO, 2018). This raises critical questions about whether farmers can continually produce food sustainably to meet this growing need. Science, Technology, and Innovation (STI) will be crucial in driving agricultural productivity and sustainability, offering solutions such as climate-smart practices, precision farming, and biotechnology. However, there are barriers related to access to technology, infrastructure, knowledge and training, and financial resources that often hinder farmers' uptake of STI.

Studies have shown that low adoption rates of CSA practices have been reported across many parts of sub-Saharan Africa (Antwi-Agyei & Amanor, 2023). Throw *et al.*, (2017) reports that most countries in SSA do not have the institutional mechanisms, coordination and infrastructure globally required to be STI ready. Ouédraogo *et al.*, (2019) adds that while most farmers are aware of many CSA technologies and practices, only a small number of the farmers are adopting the practices.

Even though CSA practices are context-specific, farmers adoption decisions towards CSA practices are triggered by factors like their socio-demographic characteristics, farm and economic factors, technological, institutional, and social factors (Sarker & Wu, 2019). Education level of farmers, extension contact, accessing climate variability information, access to irrigation facilities, and social group participation were found to be significant in influencing the adoption decision of CSA practices (Wakweya, 2023).

Further, Ogunyiola *et al.*, (2022) found the adoption of multiple CSA practices to be determined by the net benefit farmers gained. Also, smallholder farmers may find it challenging to adopt CSA practises as their inability to get access to extension services, may limit their understanding for the need of CSA (Ogisi *et al.*, 2023). Other factors such as the scarcity of improved crop varieties, access to credit and quality information are institutional factors (Sarker & Wu, 2019). Kombat *et al.*, (2021) explains that farmer-to-farmer information sharing was essential to influencing farmers' attitudes towards technology adoption and presents an opportunity to increase CSA adoption. Studies such as Boudalia *et. al*. (2024) identify significant gender gaps in adopting CSA technologies, caused by policy legislation, financial resources, social and cultural taboos, and technical determinants such as climate information access.

Table 4: Summary of factors hindering uptake of climate smart technologies and innovations

Barriers	Key factors
Institutional and Policy Barriers (Throw et al., 2017)	Weak Governance Structures
	Lack of Policy Coordination
Financial Barriers (Sarker & Wu, 2019); (FAO, 2020)	High Costs of Technology
	Limited Funding
	Inadequate investment in research and innovation
Structural barriers (Gumucio et al., 2020)	Sparse connectivity
	Not be locally tailored, context-specific or translated into local languages
Technical and Capacity Barriers (Ouédraogo et al., 2019)	Limited Research and Development
	Inadequate Technical Expertise
	Limited digital literacy
Social and Cultural Barriers (Partey et al., 2018)	Resistance to Change
	Lack of Awareness and Education

Enablers

Enabling the widespread adoption of climate smart science, technologies and innovations in agriculture requires a multi-faceted approach. Key enablers include:

Policy Support and Governance: Strong, coherent policies and frameworks are crucial for integrating STI into agricultural systems. These policies should foster innovation, streamline access to climate finance, and create conducive environments for STI adoption across regions.

Capacity Building and Knowledge Transfer: Enhancing farmers' capacity through training and education initiatives is essential for scaling climate-smart practices. Extension services and technology transfer mechanisms can empower farmers to adopt innovations that improve resilience and productivity.

Public-Private Partnerships (PPP): Collaboration between governments, private sector actors, and research institutions can unlock greater investments in agricultural innovation. These partnerships provide opportunities to develop, test, and scale new technologies that are tailored to the unique challenges faced by African farmers.

Access to Finance and Climate Funding: Addressing the financial barriers to STI adoption is critical. International climate funds, donor organizations, and development banks, such as the World Bank and the Food and Agriculture Organization (FAO), play a significant role in closing the Climate-Smart Agriculture (CSA) funding gap. For instance, between 2016 and 2018, the World Bank supported eighty-three CSA projects in Africa, investing US$3.8 billion. The Food and Agriculture Organization (FAO) pioneered the concept of Climate-Smart Agriculture (CSA), and as well provides technical guidance, policy support, and investment frameworks to help countries build resilience, adapt to climate change, and ensure a food-secure future for generations to come (Williams *et al.*, 2015). The World Bank and the CCAFS program launched a set of Country CSA profiles that provides critical stocking of ongoing and promising practices for the future and for institutional and financial enablers for CSA adoption (Lipper *et al.*, 2017). Also, the FAO and World Bank formally developed CSA in 2010 as an approach to guide the transformation of commercial and subsistence agricultural systems in developing countries (Chandra *et al.*, 2017)

Youth Engagement: Given that agriculture employs up to 60% of Africa's population, much of which is youthful, engaging young people in agriculture is pivotal (Mungai *et al.*, 2019). Young people are increasingly familiar with Information and Communication Technologies (ICTs), such as mobile phones, which can accelerate the integration of technology into agricultural practices. Creating platforms for youth participation not only drives innovation but also prepares the next generation to lead sustainable agricultural development.

International Climate Funds and Strategic Alignment: Studies like Scherr *et. al.*, (2014) argue that due to the diverse sources of funding for climate smart activities, on the ground, implementing the different projects could lead to inefficiencies because the projects or activities are related. Climate funds, while plentiful, can sometimes lead to inefficiencies when multiple, overlapping projects are implemented without alignment. Strategic use of climate finance within an agricultural investment framework could enhance coordination and support local institutions in achieving production, livelihood and ecosystem benefits more efficiently.

Conclusions

Thinking of STI in a sustainable future for agriculture in Africa

Sustaining increased agricultural output in the future will necessitate that farmers produce more with the same or fewer resources. According to Campbell *et al* (2023) and Williams *et al* (2021), this requires:

A commitment to funding knowledge and research, which are essential for developing innovative food systems that leverage science and technology to drive productivity growth.

Achieving policy coherence is crucial. Policies must be inclusive, locally-led, equitable, integrated, and supported by strong political will.

Enhancing data flow is also vital to fill gaps in regular weather station data, agricultural statistics, and census information, enabling informed decision-making. Closing finance gaps is imperative by increasing financial flows by billions of dollars annually from both public and private sectors, alongside enhancing direct access to multilateral funds. Through these combined efforts, the agricultural sector can effectively adapt to future challenges and ensure food security.

Recommendations

African countries can significantly advance climate-smart science, technologies and innovative initiatives, for enhanced agricultural resilience and sustainability in the face of climate change challenges in future. Implementing the following recommendations would advance climate-smart agriculture (CSA) in Africa, and would address key barriers to effective implementation and scaling of CSA practices while creating an enabling environment for farmers to adopt sustainable practices to foster resilience in agricultural systems, ensuring food security and sustainable livelihoods in future. The following are proposed:

i. Enhancing Research and Development: Prioritize funding for research and development in science, technology, and innovation (STI) to expand climate-smart agriculture (CSA) practices and address emerging climate challenges effectively.
ii. Strengthening Public-Private Partnerships (PPPs): Foster collaboration between governments, research institutions, and the private sector to facilitate CSA adoption and scaling, leveraging the expertise and resources of each stakeholder.
iii. Increasing Strategic Public Sector Investment: Allocate targeted public sector funding towards agriculture-specific infrastructure that supports CSA practices and ensures an enabling environment for farmers.
iv. Leveraging Private Sector Investment: Develop compelling business cases and documentation

of successful CSA practices to attract private investment, alleviating the financial burden on public sources and bridging the existing funding gap.

v. Promoting Innovation Hubs and Technology Startups: Encourage the establishment of innovation hubs and technology startups focused on providing digital platforms for CSA extension, market access, and traceability services, thus enhancing farmers' access to essential resources.

vi. Implementing Comprehensive Capacity-Building Programs: Provide training and capacity-building opportunities for all stakeholders, including agricultural extension agents, farmer organizations, and local leaders, to enhance their ability to support CSA adoption among farmers.

vii. Enhancing Data Collection and Information Sharing: Improve access to relevant agricultural data, including weather patterns and farming practices, to empower farmers with the information necessary for effective climate-smart farm management.

viii. Building Trust Among Stakeholders: Foster trust and open communication between farmers, technology providers, and other stakeholders to reduce skepticism regarding CSA practices and ensure successful implementation.

ix. Demonstrating Tangible Impacts: Ensure that CSA projects extend beyond pilot phases and demonstrate measurable impacts to encourage wider adoption among farmers and stakeholders

Call to action

The successful implementation of climate-smart agriculture (CSA) strategies improves when stakeholders actively participate in the planning and execution process (Makate, 2019). The roles of stakeholders can vary in the implementation of CSA (Davila *et al.*, 2024). For instance, Ghimire *et al.* (2022) highlighted that government entities prioritize adaptation and mitigation investment areas through national and subnational policies. The private sector identifies investment opportunities and facilitates technology transfers to farmers, while non-profit organizations advocate for farmers' needs and educate them on best practices. The following call to action is targeted at relevant stakeholders across government, the private sector, and beneficial farmers in promoting climate-smart science, technologies, and innovations:

i. Governments and Policymakers

Action 1: Enhance policy reviews and improve policy coordination

Action 2: Enhance finance flows and resource mobilization

Action 3: Strengthen local, national and regional institutions to support implementation of STI in CSA

Action 4: Identify strategies and enabling environment for continuous development of CSA technologies and innovations

Action 5: Partnerships for delivery through public-private partnerships.

ii. Research and academia

Action 1: Identify key areas of concern and create and test models of representativeness; inclusivity and cost-effectiveness

Action 2: Share research results through accessible platforms to inform policy and practice

Action 3: Collaborate with diverse stakeholders to ensure accuracy and relevance.

Action 4: Harness stakeholder inputs to ensure acceptability of technologies and innovations developed

Action 5: Capacity development in STI for improved climate actions

iii. Practitioners, Entrepreneurs,and International Development Organizations

Action 1: Engage all relevant stakeholders in design and support of projects that enhance uptake of STI

Action 2: Invest in capacity building initiatives such as innovation hubs and technology startups

Action 3: Develop and support innovative financing models

Action 4: Promote and facilitate partnership to address STI challenges collaboratively

Action 5: Create compelling business cases of past strategies, emphasizing economic viability and environmental benefits to encourage uptake.

iv. Beneficiaries - Farmers/Communities

Action 1: Identify diverse needs and vulnerabilities within communities

Action 2: Accept and participate in inclusive engagement strategies and inclusive forums

Action 3: Build capacities for knowledge and skills necessary to adapt to climate change and CSA practices and technologies

Action 4: Share evidence of impact of projects benefitted from.

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Commissioned Study 2

Assessing the Reliability of Weather Forecasts for Production Decisions and the Impact of Climate-Smart Agricultural Practices on Income and Rice Variety Adoption Among Smallholders in Kwara State, Nigeria

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Abstract

Climate change poses a significant threat to global crop and livestock production, necessitating efforts such as accurate weather forecasting and the adoption of climate-smart agricultural (CSA) practices to mitigate risks. This study examines how their characteristics and attributes influence smallholder farmers' perceptions of weather forecast reliability for production decisions. Additionally, it evaluates the impact of CSA practices on farmers' income and rice variety adoption. A cross-sectional survey of 400 farmers across 167 major rice-growing communities in Edu Local Government Area, Kwara State, Nigeria, was conducted. Data was analyzed using ordered probit and multivariate regression models. The results indicate that greater rice farming experience and access to weather stations significantly increase the likelihood of farmers perceiving weather forecasts as having low to medium reliability.

Conversely, the same factors decrease the probability of farmers perceiving forecasts as highly reliable. Subsequently, CSA practices positively and statistically significantly impacted farmers' income, and the number of rice varieties adopted. These findings indicated that while farmers' experience and access to weather information complement production decisions, the intensified use of CSA practices enhances income and promotes the adoption of diverse rice varieties, contributing to regional agricultural resilience.

Keywords: Climate-smart agriculture (CSA), Income impact, Production decisions, Rice variety adoption, Weather forecast reliability

Introduction

Agriculture has long served as a cornerstone of livelihood for many economies, particularly in Africa. It provides employment, generates income, and contributes to food security, poverty reduction, and overall welfare. However, agricultural productivity is highly dependent on climate conditions, which influence vegetation patterns, crop types, yields, and the duration of growing seasons. (Saadu *et al.*, 2024). As a result, any significant shifts in climate pose substantial challenges to food security, especially in developing countries (Bouteska *et al.*, 2024). Climate change has emerged as a global concern, affecting agricultural production systems through rising temperatures and increasingly erratic weather patterns (Ani *et al.*, 2022). These changes disrupt food production and supply chains, threatening agriculture's vital role in providing sustenance and industrial inputs (Saleem *et al.*, 2024).

In response to the threats posed by climate change, countries have adopted various strategies, including improving the accuracy of weather forecasts and promoting Climate-Smart Agriculture (CSA) practices. CSA technologies aim to increase resilience, improve productivity, and reduce greenhouse gas emissions (Zheng et al., 2024). Despite these interventions, smallholder farmers, who form the pillar of agricultural production in many developing economies, remain concerned about the reliability of weather forecasts for making critical production decisions. Many smallholders continue to rely on their experience with weather variability, traditional knowledge, and indigenous farming practices to manage climate risks (Agyekum et al., 2022). Indigenous knowledge, described by File & Nhamo (2023), postulates that the collective understanding of weather patterns, plants, animals, and agricultural systems has proven essential in building resilience among smallholders and sustaining household food production.

Smallholder farmers in Africa have long employed indigenous knowledge systems to adapt to climate change, reducing their vulnerability to weather shocks (Oladele & Amara, 2024). These adaptation strategies often involve traditional practices such as using organic manure, intercropping, planting indigenous and improved seed varieties, and employing natural pest control methods, such as neem leaves and ashes. Despite the availability of weather forecasts from government and non-governmental agencies, many smallholders remain skeptical of their reliability. This skepticism has strengthened their reliance on traditional farming practices, which they perceive as more dependable in coping with climate uncertainties.

Although several studies have explored the impacts of climate change on crop and livestock production (Ani *et al.*, 2022; Bouteska *et al.*, 2024; File and Nhamo, 2023; Oladele & Amara, 2024; Saadu *et al.*, 2024), still, limited attention is paid to smallholders' concerns about the reliability of weather forecasts and how these concerns influence their production decisions. This study aims to bridge this gap by assessing how their personal characteristics and farming experiences shape farmers' perceptions of weather forecast reliability. Additionally, the study evaluates the effects of smallholders' traditional farming practices on their income levels and the adoption of rice varieties. The findings will contribute to a deeper understanding of how climate-smart agricultural practices and indigenous knowledge intersect to shape smallholder farming outcomes in Kwara State, Nigeria.

The principal objective of this study is to assess the reliability of weather forecasts for production decisions and to evaluate the impact of climate-smart agricultural (CSA) practices on income and rice variety adoption among smallholders in Kwara State, Nigeria. The following specific objectives were used to accomplish the principal objective: 1. examine smallholder farmers' perceptions of the reliability of weather forecasts for agricultural production decisions; 2. analyze how farmers' characteristics and experiences influence their perceptions of weather forecasts; 3. assess the impact of smallholders' adoption of climate-smart agricultural practices on their income levels; 4. investigate the relationship between using CSA practices and adopting improved rice varieties among smallholders.

This study provided valuable insights into the role of reliable weather forecasts and CSA practices in improving agricultural productivity and resilience among smallholders in Kwara State, Nigeria.

Literature Review

Climate Change Variability and Climate-Smart Agricultural (CSA) Practices

There is a strong link between agricultural productivity and climatic conditions, which determines crop yields, vegetation patterns, and the duration of cropping seasons. Any climate change can significantly disrupt food production and the supply of raw industrial materials. Over the past few decades, climate change has accelerated across many regions, and greenhouse gas emissions continue to raise serious concerns about food security and global agricultural productivity (Bouteska *et al.*, 2024). Smallholders relying heavily on rainfed agriculture are particularly vulnerable to climatic changes, such as irregular rainfall patterns, prolonged droughts, and extreme weather events (Tofu *et al.*, 2022).

Studies have documented the uncertainties associated with climate change, especially concerning future rainfall, floods, and droughts (Bolan *et al.*, 2024; Chan *et al.*, 2021). The Intergovernmental Panel on Climate Change (IPCC) (2007) has forecasted that sub-Saharan Africa will experience temperature increases higher than the global average, which may lead to increased soil moisture loss, unpredictable rainfall, more intense crop diseases, and frequent extreme climatic events (Bedair *et al.*, 2023). There is the expectation that these climatic changes exacerbate smallholders' vulnerabilities further, particularly in Africa, with projected crop yields to decline by 10–20% by 2050 (Ayanlade *et al.*, 2022).

The promotion of several CSA practices helps farmers adapt to climate variability. These include conservation agriculture, agroforestry, minimum tillage, intercropping, and improved seed varieties (Tariku & Kebede, 2024). Agroforestry, for instance, integrates trees with crops to improve soil fertility, reduce erosion, and enhance water retention, contributing to adaptation and mitigation of climate change (Rolo *et al.*, 2023). Likewise, minimum tillage, a key component of conservation agriculture, reduces soil disturbance, enhances organic matter, and improves water infiltration, leading to better yields and sustainable farming systems (Page *et al.*, 2020).

These CSA practices, which focus on sustainable income generation, soil fertility improvement, and water conservation (Zheng *et al.*, 2024) have boosted resilience to climate change. Our study explores how smallholders in Kwara State adopt these practices and perceive their effectiveness in mitigating the adverse impacts of climate change on rice production.

Smallholders' Perceptions of Climate Change

Smallholder farmers' perceptions of climate change are vital in designing their adaptive strategies and decision-making processes. Research indicates that smallholders perceive changes in climate change through their lived experiences, although these perceptions may not always align with meteorological data (Ayanlade *et al.*, 2022). According to Yamba *et al.* (2019), in Ghana, smallholders' perceptions of climate variability were mainly consistent with regional climate data, although the researchers observed certain discrepancies. Information dissemination from family, government, and media sources, particularly television and radio, significantly shaped these perceptions.

In South Africa, Rapholo and Diko Makia (2020) found that about 64% of smallholders correctly perceived climate variability, which supports the meteorological evidence. Factors such as age, education, and access to information influenced their ability to perceive these changes. Meanwhile, Asefa (2024) underscores that farm size and livestock ownership were critical factors in adopting adaptation strategies in Ethiopia. Notably, smaller farm sizes hindered farmers' ability to cope with climate change, while greater livestock ownership increased the likelihood of adopting CSA practices.

A study by Kidane *et al.* (2022)either separately or together, shape the adaptation responses of smallholder farmers in the Raya Azebo district of Ethiopia. Their adaptation responses include adjusting planting periods, crop diversification, changing crop types, adopting improved seeds, using irrigation, conducting migration, participation in wage employment, selling local food and drinks, and owning small shops. We found that these adaptation responses were motivated by various climatic (e.g., drought and rainfall variability in Ethiopia emphasized that extreme events such as droughts reinforce pessimism about the future and deeply influence smallholder perceptions. Their research noted that non-climatic factors, such as socioeconomic and political changes, also shape farmers' attitudes toward climate change and adaptation options.

Our study builds upon this body of literature by assessing smallholders' perceptions in Kwara State, Nigeria, particularly regarding the reliability of meteorological forecasts and their implications for production decisions. Understanding how smallholders perceive these forecasts and how they influence their adoption of climate-smart agricultural practices will provide critical insights into the effectiveness of adaptation strategies in this region.

Theoretical Framework: Decision Theory and Climate-Smart Agriculture Adoption

This study is grounded in decision theory, which examines how individuals make choices under uncertainty. Smallholders face considerable uncertainties regarding climate variability, market conditions, and resource availability. Decision theory posits that farmers make production decisions based on expected utility maximization, weighing the potential risks and benefits of different actions (Bocquého *et al.*, 2014).

In the context of CSA adoption, smallholders are likely to adopt practices that they perceive as offering the most significant utility in reducing risks associated with climate change, such as yield variability and income fluctuations (Saadu *et al.*, 2024). However, the decision to adopt such practices is also influenced by access to resources, extension services, and information about climate variability (Nyang'au *et al.*, 2021). This framework helps explain why smallholders' adoption of CSA practices varies across regions and demographic groups.

Reliability of Weather Forecasts for Production Decisions

Accurate weather forecasts are essential for smallholders to make informed production decisions, particularly in regions with erratic rainfall patterns. Farmers rely on meteorological predictions to determine planting times, irrigation needs, and pest control measures (Paparrizos *et al.*, 2023). However, the reliability of these forecasts can significantly impact farmers' confidence in using them as decision-making tools.

Previous studies suggest that smallholders often perceive meteorological forecasts as unreliable, prompting skepticism about their use in planning agricultural activities (Paparrizos et al., 2023). In Kenya, for instance, some farmers distrusted weather forecasts due to discrepancies between predictions and actual outcomes (Muita *et al.*, 2021). Conversely, there is evidence that access to reliable and location-specific weather forecasts improves farm-level decision-making and productivity (Paparrizos *et al.*, 2023).

In this study, we investigated how smallholders in Kwara State perceive the reliability of weather forecasts and how these perceptions influence their adoption of CSA practices. Understanding these dynamics is critical for designing effective extension services and ensuring smallholders can access accurate and actionable climate information.

Impact of CSA Practices on Income and Rice Variety Adoption

Adopting climate-smart agricultural practices has been linked to increased income and food security among smallholder farmers (Saadu *et al.*, 2024). Studies suggest minimum tillage, agroforestry, and improved seed varieties can enhance crop resilience to climate variability, stabilizing farmers' income streams (Mohamed Shaffril *et al.*, 2024). Furthermore, access to improved rice varieties, which are more tolerant to drought and disease, has increased yields and income in various African countries (Mishra *et al.*, 2022).

However, barriers to adopting these practices remain, including limited access to financial resources, inadequate extension services, and a need for more awareness about the benefits of CSA practices (Pedersen *et al.*, 2024). Our study explores how CSA practices impact income levels and rice variety adoption among smallholders in Kwara State, highlighting the key factors that drive or inhibit these outcomes.

Research Gap: Although previous studies have examined the adoption of climate-smart agricultural practices and their effects on farm productivity, there is limited empirical evidence on the combined impact of weather forecast reliability and CSA adoption on smallholder decision-making and economic outcomes in Kwara State, Nigeria. Furthermore, most researches have focused on crop yield rather than farmer income and varietal adoption. This study addresses these gaps by assessing how weather forecasts influence production decisions and exploring CSA practices' role in shaping income and adopting improved rice varieties. It also incorporates socio-demographic factors, including access to extension services, which have been underexplored in similar contexts. This research will provide valuable insights into the practical aspects of integrating meteorological data with climate-smart practices and offer policy recommendations to improve the resilience of smallholder farmers in Nigeria against climate risks.

Conceptual Framework

This study explores the relationship between smallholder farmers' perceptions of weather forecast reliability, their agricultural decision-making, and adopting climate-smart agricultural (CSA) practices. It also investigates the influence of these factors on farmers' income and the adoption of improved rice varieties. The framework combines multiple dimensions of agricultural decision-making, examining how information sources, the reliability of weather forecasts, and adopting climate-smart technologies influence vital economic outcomes.

The CSA critical components in this study are as follows: 1. Weather Forecast Reliability, which includes smallholder farmers' perceptions of the accuracy and reliability of weather forecasts for production decisions. The indicators of weather forecast reliability are the sources of weather forecast information, such as media, extension services, family, and friends. The second CSA key component is 2. Climate-Smart Agricultural Practices (CSA), whose indicators are adopting CSA practices, including mulching, agroforestry, and minimum tillage, aim to improve farm productivity and resilience to climate variability. The other CSA indicators influence adoption: farm size, access to agricultural extension services, education, and income. The third key CSA component is the 3. Rice Variety Adoption, which indicators influence smallholders' adoption of improved rice varieties, and the Impact of CSA practices on adoption rates and farmers' decision-making processes. The fourth key component is 4. Economic impact which includes indicators like the impact of CSA practices and weather forecast reliability on household income and income variations resulting from climate adaptation and resilience strategies. Subsequently, the fifth key CSA component is the 5. External influences are social, economic, and environmental indicators that shape farmers' perceptions and adoption of innovations, including climate variability, access to agricultural extension services, and government interventions.

The following hypotheses guided our study: (i). The perception of weather forecasts as being reliable significantly influences smallholder farmers' likelihood of using them in making production decisions; (ii) Adopting climate-smart agricultural (CSA) practices significantly improves the income of smallholder farmers; (iii) Adopting CSA practices significantly influences smallholder farmers' likelihood of adopting improved rice varieties; (iv) External factors, such as access to extension services and socio-demographic characteristics, significantly influence farmers' adoption of CSA practices and improved rice varieties.

Methodology

Study Area, data and sampling

The researchers conducted the study in Kwara State (specifically, Edu Local Government Area-LGA), north-central Nigeria. Edu LGA is a large LGA in Kwara State with up to 167 villages or rural/farming settlements. It is also a significant rice-farming LGA in Kwara State. Rice is, however, grown with other crops. The primary vegetation of the area is the guinea savanna, which favors the cultivation of the land for other arable crops such as maize, cowpea, guinea corn, yam, and a few trees planted scattered across the LGA. Farming households in the LGA also raise farm and domestic animals such as cattle, donkeys, goats, sheep, chickens, and guinea fowl. There is the observation that many rice farmers in Edu LGA adopt traditional CSA practices, which informed the purposive selection of the LGA for this study. Using a multistage random selection approach, this study surveyed a cross-section of 400[1] arable crop farmers across selected villages in the LGA. Input and output data in actual and value terms were collected. The research utilized questionnaires distributed to household heads in randomly selected villages. Other elucidative variables were socioeconomic and demographic (age, household size, gender, educational levels, farming experience, rice farming experience, and farm size). The study generated information on the CSA practices adopted by the farmers, their numbers, and farmers' perceptions of the reliability of meteorological forecasts and predictions for farming and production decisions.

Data analysis

Data was analyzed using both descriptive and inferential statistics. The inferential statistics employed were Ordered probit and multivariate regression models.

Terciles, for example, were generated: a lower tercile representing low reliability, a middle tercile for moderate reliability, and an upper tercile for high reliability of meteorological forecasts and predictions by farmers. The study derived these data from a section of the questions that required the farmers to indicate what they felt (on a scale of 1 = lowly, 2 = moderately, and 3 = highly reliable) about how reliable meteorological predictions were for their farming and production decisions.

An ordered probit regression was then run to identify the factors influencing farmers' perceptions of the reliability of meteorological predictions. The study used an ordered probit to model relationships between a polytomous response variable with an ordered structure and a set of regressor variables. Using the reliability scores/levels (as computed in Section 3.2.1) from the terciles of reliability of the meteorological predictions, researchers grouped the sampled farmers into low, moderate, and high-reliability categories. The standard ordered probit model is widely used to analyze discrete data of this variety, built around a latent regression of the following form:

$$y^* = x' \beta + \varepsilon \qquad (1)$$

Where x and β are standard variables and parameter matrices, respectively, and ε is a vector matrix of normally distributed error terms. Predicted grades (y^*) are unobserved. We do, however, observe the following:

$$y = 0 \text{ if } y^* \leq 0 \qquad (2)$$

$$y = 1 \text{ if } 0 < y^* \leq \mu 1 \qquad (3)$$

$$y = 2 \text{ if } \mu_1 < y^* \leq \mu_2 \qquad (4)$$

1 An appropriate sample size of 400 had early been determined using 'Confidence Interval level' approach (Hazra, 2017).

Where μ1 and μ2 are the cut-off points, i.e., the threshold variables in the probit model. The unknown threshold variables indicate the discrete category into which the latent variable falls. They are determined using the maximum likelihood estimation procedure for the ordered probit. This study adopted the ordered probit used in the studies of Johnston et al. (2020) and Olarinde et al. (2020) at national and household levels, is on the decline because traditional capital (physical, natural, human and financial.

The likelihood of a benefit received by an individual is:

$$L = [\Phi (0 - X_i\beta)]^{zi1} [\Phi (\mu_1 - X_i\beta) - \Phi (0 - X_i\beta)]^{zi2} [1 - \Phi (X_i\beta - \mu_1)]^{zi3} \quad (5)$$

Z_{ij} =1 if y_i = j; 0 otherwise for j = 0.1 and 2

For the i^{th} individual, y_i is the observed outcome, and X_i is a vector of explanatory variables. The researchers typically estimated unknown parameters βj by maximum likelihood. Y = reliability of meteorological forecast, (0 = low reliability, 1 = moderate reliability, 2 = high reliability). X1 = age (years), X2 = schooling years, X3 = level of education (years), X4 = Household size (number), X5 = Farming experience (years), X6 =rice farming experience (years), X7 = farm size (hectares), X8 = membership of cooperative society (1=yes, 0=otherwise), X9 = membership of farming association (1=yes, 0=otherwise), X10 = closeness to research station (1 = yes, 0 = otherwise), X11 = closeness to weather station (1 = yes, 0 = otherwise).

This research used multivariate regression: Multivariate regression (mvreg) analyzed the effects of CSAs on two [2] welfare indicators, (i) income and (ii) assets/wealth-number of adopted rice varieties (Grzelak, 2022).

The Revenue (income) is generated and endowed by the sampled farmers in the study area. The model used here has features similar to those of the OLS regression model (Akanbi et al., 2024). The output from the mvreg command looks much like the output from the regress command, except that the output is for two equations (one for each outcome measure) instead of one. In addition to looking like the output from an OLS regression, the output is interpreted much like the output from an OLS. As the name implies, multivariate regression is a technique that estimates a single regression model with more than one outcome variable. When there is more than one predictor variable in a multivariate regression model, the model is a multivariate multiple regression. The model is specified like OLS only that the dependent variable is more than one. The outcome variables should be moderately correlated for the multivariate regression analysis to make sense. In this study, the assumption is that income and assets accumulated from that place are moderately correlated. The models are as specified in equations (6) and (7).

$W_i = \alpha_i Z_i + \mu_i$ and W2 are the income and asset, (6)

$$W_1, W_2 = \alpha_i Z_i + \mu_i \quad (7)$$

Where W_i= Individual farmer's welfare indicator (income and asset), Z_i represents the vector of explanatory variables. The W_1 and W_2 are the income and asset, respectively, while explanatory variables are as defined in 3.2.2.

Identified CSA practices and their components

A full complement of CSA practices and their components are listed and described in the FAO's CSA sourcebook (FAO, 2013)as well as limitations. It aims to help decision makers at a number of levels (including political administrators and natural resource managers. Subsequently, the study identified the following CSA practices and their components used by the sampled rice farmers (Table 1). These were: (i) Agronomic Practices (improved seeds, crop rotation, intercropping, cover crops); (ii) Integrated Soil Fertility Management (manure, inorganic fertilizer); (iii) Tillage and Residue Management (conservation tillage, incorporation of crop residues); (iv) Water Management

2 Welfare indicators: Income (net revenues) and Assets/Wealth-number of rice varieties adopted.

(irrigation, terracing, contouring); (v) Integrated Pest Management (cultural application, biological control, chemical control) and (vi) Agroforestry (intercropping crops and trees, live fencing). Most sampled farmers practiced mixed components from and across the common and available CSAs in the study villages. From our investigation, some farmers did not indicate their use of any of these practices, which implies some had zero adoption of the CSA practices. However, some farmers adopted up to an average of 12 of the CSA components.

Table 1: Identified Climate Smart Agricultural Practices in the Study

CSA Practices		Components
i.	Agronomic Practices	Improved seeds, crop rotation, intercropping, cover crops
ii.	Integrated Soil Fertility Management	Manure, Inorganic fertilizer
iii.	Tillage and Residue Management	Conservation tillage, incorporation of crop residues
iv.	Water Management	Irrigation, terracing, contouring
v.	Integrated Pest Management	Cultural application, biological control, chemical control
vi.	Agroforestry	Intercropping crops and trees, live fencing

Source: Authors' compilation and as adapted from (FA0, 2013)

Results and Discussion

Categories of Sampled Farmers Based on Perception of Meteorological Forecast Reliability

The research categorized the farmers into three groups based on their perception of the reliability of meteorological forecasts. The results showed that 11.75% of the farmers had a low perception of reliability, 40.25% had moderate confidence, and 48% believed the forecasts were highly reliable (Table 2). These results indicate that nearly half of the respondents find meteorological forecasts trustworthy, which has important implications for their decision-making regarding agricultural practices. This categorization is consistent with previous studies suggesting that various socioeconomic and experiential factors influence farmers' perceptions of meteorological forecasts (Ayanlade *et al.*, 2022). This observation also underscores the need to improve forecast reliability and enhance communication channels to boost farmer trust and adoption of climate-smart agricultural practices (CSA).

Table 2: Distribution of Respondents by reliability of meteorological Prediction

Meteorological Reliability	Frequency	Percent
Low	47	11.75
Moderate	161	40.25
High	192	48.00
Total	400	100.00

Number of CSA Components Adopted by Respondents

The results (Table 3) showed that only a low percentage (6%) of farmers had yet to adopt any CSA components, with similar percentages across the reliability categories. However, this may not imply a complete lack of CSA adoption; it could reflect limited awareness or a misunderstanding of what constitutes CSA components. This observation aligns with findings by Zagre *et al.* (2024)developing appropriate climate-smart technology (CST, who noted that farmers' awareness often precedes the adoption of climate adaptation strategies.

Up to 21% of farmers had adopted nine CSA components, with relatively similar adoption rates across the three perception groups. The highest number of CSA components adopted by any farmer was 12, as indicated by 13.75% of the pooled sample and a slightly higher percentage among the moderate reliability group (16.15%). The values suggest a reasonably high level of engagement with CSA practices, particularly among those with a more moderate view of forecast reliability.

Looking at individual CSA practices (Table 4), integrated soil fertility management recorded the highest level of component adoption, with 46.75% of farmers adopting at least three components. Other practices, including agronomic and water management, adopted fewer components, indicating that CSA adoption is not uniform across different areas. These findings are consistent with previous studies highlighting the selective nature of CSA adoption, often dependent on farmers' specific needs, access to resources, and perceived benefits (Kangogo et al., 2021)with serious impacts on smallholder farmers' food security and livelihoods. Climate-smart agriculture (CSA).

Table 3: Number of CSA practices adopted by respondents: Pooled Data and by Meteorological Reliability Level

Meteorological Reliability Level								
Total No. of CSA components adopted per rice farmer	**Pooled Data**		**Low**		**Moderate**		**High**	
	Frequency	**Percent**	**Frequency**	**Percent**	**Frequency**	**Percent**	**Frequency**	**Percent**
0	24	6	4	8.51	10	6.21	10	5.21
1	1	0.25	-	-	1	0.62		
2	3	0.75	-	-	2	1.24	1	0.52
3	22	5.50	2	4.26	9	5.59	11	5.73
4	8	2.00	2	4.26	3	1.86	3	1.56
5	32	8.00	8	17.02	9	5.59	15	7.81
6	26	6.50	2	4.26	13	8.07	11	5.73
7	35	8.75	5	10.64	15	9.32	15	7.81
8	58	14.50	2	4.26	25	15.53	31	16.15
9	83	20.75	9	19.15	30	18.63	44	22.92
10	25	6.25	5	10.64	7	4.35	13	6.77
11	28	7.00	2	4.26	11	6.83	15	7.81
12	55	13.75	6	12.77	26	16.15	23	11.98
Total	400	100	47	100.00	161	100.00	192	100.00

Table 4: Number of CSA components (per practice) adopted by respondents: Pooled Data and by Meteorological Reliability Level

CSA Practices	No. adopted per practice	Total		Low		Moderate		High	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Agronomic Practices	0	75	18.75	10	21.28	30	18.63	35	18.23
	1	215	53.75	22	46.81	71	44.10	122	63.54
	2	110	27.50	15	31.91	60	37.27	35	18.23
Integrated Soil Fertility Management	0	44	11.00	7	14.89	17	10.56	20	10.42
	1	25	6.25	3	6.38	9	5.59	13	6.77
	2	144	36.00	15	31.91	49	30.43	80	41.67
	3	187	46.75	22	46.81	86	53.42	79	41.15
Tillage and Residue Management	0	91	22.75	14	29.79	26	16.15	51	26.56
	1	150	37.50	17	36.17	61	37.89	72	37.50
	2	159	39.75	16	34.04	74	45.96	69	35.94
Water Management	0	84	21.00	11	23.40	33	20.50	40	20.83
	1	131	32.75	15	31.91	54	33.54	62	32.29
	2	185	46.25	21	44.68	74	45.96	90	46.88
Integrated Pest Management	0	30	7.50	5	10.64	10	6.21	55	7.81
	1	97	24.25	6	12.77	68	42.24	23	11.98
	2	273	68.25	36	76.60	83	51.55	154	80.21
Agroforestry	0	89	22.25	10	21.28	53	32.92	26	13.54
	1	152	38.00	18	38.30	58	36.02	76	39.58
	2	159	39.75	19	40.43	50	31.06	90	46.88

Descriptive Statistics of the Socio-demographic and Economic Variables

Table 5 provides the socioeconomic profile of the farmers. On average, farmers had 19 years of rice farming experience and 23 years of total farming experience, reflecting a relatively seasoned group. The mean farm size was 2 hectares, indicating that these are smallholders typical of Nigeria's agricultural landscape. Membership in cooperatives (40.25%) and farmer associations (73.75%) is relatively high, which could facilitate access to CSA practices and other resources.

Proximity to research and weather stations was significant for 74.50% and 46% of the farmers, respectively. As discussed later, this proximity likely plays a role in CSA adoption and meteorological perception, in addition to aligning with the study of Olasehinde et al. (2022) on the Performance of Nigerian Rice Farms from 2010 to 2019. Interestingly, despite the farmers' relatively low levels of formal education (an average of 2 years of education), they have integrated several CSA practices, suggesting that hands-on experience and communal knowledge-sharing may be more critical than formal education in driving adoption. This finding corroborates the work of Abegunde et al. (2020)particularly small-scale farming, is both a contributor to greenhouse gas (GHG that education through improved extension contact and exposure to mass media can strengthen integrated farm activities that bolster farm income.

Determinants of Farmers' Perception About the Reliability of Meteorological Predictions

The ordered probit model results in Table 6 highlight the significant factors influencing farmers' perception of meteorological forecast reliability. There is a negative correlation between age, rice farming experience, farm size, and membership in farmer associations with reliability perception. Older farmers and those with more rice farming experience tended to rely less on weather forecasts, likely due to a preference for traditional knowledge or a lack of trust in modern meteorological data, echoing findings from studies in Ghana and Kenya (Chepkoech et al., 2018identify the main differences in historical seasonal and annual rainfall and temperature trends between the zones, discuss differences in farmers' perceptions and historical trends and analyse the impact of these perceived changes and trends on yields, weeds, pests and disease infestation of AIVs. Design/methodology/approach: Data collection was undertaken in focus group discussions (FGD; Hirons et al., 2018).

In contrast, a positive association existed between household size, overall farming experience, membership in cooperative societies, proximity to research stations, and higher perceptions of forecast reliability. These findings align with Asare-Nuamah and Botchway (2019), who found that access to extension services and research station information significantly improves farmers' trust in climate data.

One notable finding is the impact of proximity to research and weather stations. Farmers near weather stations were likelier to have lower reliability perceptions, which could suggest mistrust in how meteorological information is communicated or processed. On the other hand, a positive association occurs between nearness to research stations and reliability, especially among farmers with high perceptions of forecast trustworthiness. This association may indicate that farmers value direct engagement with research-based data over general meteorological broadcasts.

Table 5: Descriptive Statistics of the Variable used in the regression Analysis

Variables	Frequency	Percent
Meteorological Reliability		
Low	47	11.75
Moderate	161	40.25
High	192	48.00
Total	400	100.00
Membership of Coop Society (Yes)	294	40.25
Membership of Farmers' Association (Yes)	295	73.75
Respondent is close to Research Station (Yes)	298	74.50
Respondent is close to Weather Station (Yes)	184	46.00
Variables	**Mean**	**Std. dev.**
Net Revenue (Naira per hectare)	597475.2	1313000
Number of CSA adopted	7.7375	3.199874
Respondent age (years)	41.2375	12.31748
Household Size (Number)	2.345933	0.5848551
Formal Schooling (years)	2.259505	0.5627754
Farming experience (years)	23.02	10.7589
Rice farming experience (years)	19.29	10.02983
Total holding size (hectares)	3.82575	2.604084
Land farmed (hectares)	2.2705	1.497288

Table 6: Estimates of Ordered Probit on Determinants of the Reliability of Weather Forecast (pooled and Reliability level Results)

Variable	Pooled		Reliability levels of Weather Predictions		
			Low	Moderate	High
	Coefficient	Standard error	Marginal Effects		
Age	-0.630492	0.278173**	.0099493**	0.0151897**	-0.25139**
Squared age	0.000538	0.003253**	-.0001189**	-0.0001816**	0.0003005**
Schooling years	0.0065461	0.121747	-.001033	-0.0015771	0.0026101
Household size	0.488837	0.0122029***	-.0077139***	-0.011777***	0.0194909***
Total farming experience	0.0372497	0.0144531***	-.0058781**	-0.0089741**	0.0148522***
Rice farming experience	-0.0485376	0.0143401***	.0076593***	0.0116936***	-0.0193529***
Farm size	-0.1117186	0.0409333***	.0176294***	0.0269151***	-0.0445445***

Cooperative Society	0.334574	0.1619187**	-.0527964**	-0.080605**	0.1334014**
Farmer association	-0.1904563	0.1672872	.0300544	0.0458844	-0.0759388
Research station	0.407478	0.1932425*	-.0643008**	-0.0981689**	0.1624697**
Weather station	-0.7689154	0.166748***	.1213363***	0.01852457***	-0.3065821***
/cut1	-2.194465	0.597696			
/cut2	-0.7991268	0.5922879			
Number of obs.	400				
LR chi2(11)	82.24				
Prob > chi2	0.0000				
Pseudo R^2	0.1060				

Effects of CSA Practices on Income and Rice Variety Adoption

The multivariate regression results (Table 7) reveal the impact of CSA adoption on income and the number of rice varieties adopted. CSA adoption had a statistically significant positive effect ($p<1\%$) on income for both the pooled sample and farmers, with a moderate perception of forecast reliability. These results suggest that integrating CSA practices contributes to improved economic outcomes, which aligns with prior findings on the role of CSA in enhancing productivity and resilience (Mishra et al., 2022).

The variables, such as proximity to weather stations and household size, negatively impacted income in certain groups, indicating that factors beyond CSA practices also play a crucial role in determining income. Specifically, proximity to research stations strongly affected income, underscoring the importance of accessible and reliable agricultural research in driving economic benefits for farmers.

CSA practices significantly influenced the adoption of multiple rice varieties across all perception groups, with more land and greater farming experience leading to increased adoption of new varieties. These findings suggest that CSA practices improve income and promote diversification in crop selection, which is essential for climate resilience and food security (Agyekum et al., 2022)we conduct a systematic review to synthesize the existing evidence on weather information services for the agriculture, water, and energy sectors of East and West Africa and identify priorities for future research. This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA. The mean per hectare revenue generated is [3]₦ 597475.2.

The study highlights the complex interplay between socioeconomic factors, CSA practices, and meteorological perception in determining farmers' outcomes. The findings underscore the need for targeted interventions that improve farmers' trust in meteorological data while promoting the adoption of effective CSA practices to enhance both productivity and resilience to climate change.

3 ₦ is the Nigeria (currency) Naira. One US Dollar ($) was equivalent to ₦ 423.7166 at the time of this research.

Table 7: Multivariate Regression estimates of effects of adoption of CSA practices on Revenue and number of rice varieties adopted (Assets)

Equation	Observation	Parms	RMSE	"R-sq"	F	P>F		
Income	341	12	1328293	0.0716	2.30838	0.0098		
Asset	341	12	2.087057	0.5856	42.25729	0.0000		

	Pooled		Reliability levels of Weather Predictions					
		Low		Moderate		High		
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
Income								
CSA practices	245781.1	146889.1*	281490.8	174154.8	548896.8	328316.1*	-25261.92	84155.41
Age	-5494.913	9615.397	-6879.746	14349.07	6370.908	20634.11	-12139.64	6023.459 **
Household size	-66992.71	139260.8	-44958.13	157591.6	-608458.7	364314*	192986.8	81024.6 **
Schooling	185755.8	141645.3	193713.3	154146.6	219049	306479.4	127527.5	87570.75
Farming experience	24451.82	16612.17	-23183.31	38099.63	9530.404	38472.18	40016.11	9348.441***
Rice farming experience	-155794.77	17031.49	25588.37	35364.66	19567.77	40188.24	-35486.02	10010.26***
Land size (total)	-13978.3	47453.07	52970.2	54183.74	-32328.32	99768.44	-37799.22	33052.02
Farmed size	-64721.18	78140.47	-65446.23	68391.87	-195476.8	188431	31188.59	54269.54
Cooperative society	201842.7	184790.5	-47287.44	191163.9	298775.4	374818.6	106569.6	124211.3
Nearness to a research station	-74850.54	216025.6	373355.5	247705.4	-1078472	589402.5 *	228215.6	119457.2*
Nearness to a weather station	-497849.2	202065.5**	-286711	242550.8	-742220.4	490604.4	-199891.4	129952.5
Constant	540272.9	575467.2	-63148.89	580333.1	2168628	1335864	2592.855	349667.6
Adoption of rice varieties (No.)								
CSA practices	4.761703	0.2307969***	5.110684	0.6549328 ***	5.009717	0.3827315 ***	4.362179	0.3393412***
Age	-0.0126403	0.015108	-0.0295541	0.0539616	0.0047749	0.024054	-0.0556565	0.0242885 **
Household size	-0.1008176	0.218811	-0.404381	0.5926446	0.1474137	0.4246957	-0.1561779	0.3267168
schooling	0.2082089	0.2225576	-0.2241241	0.5796892	0.5631855	0.3572755	-0.2781274	0.353113
Farming experience	0.031236	0.0261016	0.0177718	0.1432789	0.0048203	0.0448486	0.0745047	0.0376959**
Rice farming experience	-0.0369951	0.0267604	-0.020214	0.1329937	-0.0336391	0.0468491	-0.0296238	0.0403646
Land size (total)	0.1520938	0.0745598 **	0.5577845	0.2037654***	0.1884615	0.1163041	0.0622667	0.1332762
Farmed size	-0.1806038	0.1227768	-0.4786674	0.257197 *	-0.2643688	0.2196617	-0.06745	0.218832
Cooperative society	-0.2362161	0.2903488	-0.202562	0.7188978	-0.2071391	0.4369413	-0.2614913	0.5008592
Nearness to a research station	-0.067784	0.3394263	-2.349418	0.9315299**	0.1253921	0.6870904	0.1280116	0.4816892
Nearness to the weather station	-0.1427072	0.3174917	1.213129	0.9121456	-0.0877767	0.5719175	-0.2111991	0.5240096
Constant	5.890311	0.9041925	7.56757	2.182422	4.051678	1.557271	7.924637	1.409971

Conclusions

This study explored the reliability of weather forecasts for production decisions and the impact of climate-smart agricultural (CSA) practices on income and rice variety adoption among smallholders in Kwara State, Nigeria. While various efforts have globally mitigated climate risks, including improved weather forecasting and the adoption of CSA practices, smallholders remain skeptical about the effectiveness of these tools. Many farmers rely on traditional knowledge and personal experience when making production decisions, particularly during critical farming seasons.

Smallholder farmers adopted agricultural practices promoting environmental sustainability at the field level. CSA practices, tailored to specific ecological, policy, social, and economic contexts, contribute to climate resilience by enabling farmers to adapt to and mitigate the effects of climate change. However, farmers' socioeconomic and demographic characteristics, such as age, household size, farming experience, and cooperative membership, strongly influence the perception of weather forecast reliability and the subsequent adoption of these climate-smart practices.

The findings from this study indicate that higher farming experience and access to weather stations increase the likelihood of farmers perceiving meteorological predictions as less reliable. Conversely, these factors reduce the probability of farmers viewing such forecasts as highly reliable. Despite these perceptions, CSA practices significantly impact farmers' income and adoption of improved rice varieties.

Therefore, this study highlights the complementary roles of farming experience and access to weather information in shaping farmers' production decisions. The results underscore the importance of enhancing the accessibility and accuracy of weather forecasts while simultaneously promoting CSA practices to improve income and increase the adoption of diverse rice varieties. Strengthening these interventions could lead to more resilient and sustainable farming systems for smallholders in Kwara State and similar regions.

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Presentation of Research Paper

Parallel Session 1: Agroecology, biodiversity, and soil health

Impacts of CSA Options Bundle Including Fertilization, Sowing Time And Improved Varieties for Sustainable Sorghum Farming in the Sudanian Zone of Mali

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Abstract

In the agrosystems of the Sahel region, climate resilience practices that combine integrated soil fertility management, improved seeds and sowing dates, allow responding to climate variability and low soil fertility status in the region. The study was conducted at ICRISAT Samanko and IER N'Tarla research stations. The trials were conducted in split-split plot design in 2021 and 2022 growing seasons. Treatments consisted of: (1) main factor: fertilizers strategies including the control, recommended option (100 kg ha^{-1} DAP + 50 kg ha^{-1} Urea), organic amendment (5000 kg ha^{-1} cow dung) and the combined option (50 kg ha^{-1} DAP +25 kg ha^{-1} Urea + 2500 kg ha^{-1} cow dung), (2) subfactor: 2 sowing dates (SWD1: medium and SWD2: late sowings times) with 3 weeks interval, (3) sub-sub factor: 3 sorghum varieties (Soubatimi, Jakunbe and Pablo). The results revealed that SWD1 resulted in higher stover and grain yields, as well as improved Water Use Efficiency (WUE) for grain yield compared to SWD2. SWD1 outperformed SWD2 in terms of stover and grain yields, with a 65% and 30% increase, respectively. The organo-mineral fertilization outperformed all the other fertilization strategies for all the studied parameters (biomass and grain yields and WUE). Pablo exhibited the highest performance at Samanko with grain yield of 1765 and 2740 kgha^{-1} in the 2021 and 2022 seasons respectively. For the study's agroecological zones, we recommend Pablo and Soubatimi for SWD1, and Jakunbe for SWD2, all with the organo-mineral fertilizers application.

Introduction

Sorghum (Sorghum bicolor (L.) Moench) occupies a major niche in many semi-arid subtropical farming systems due to its low cost of production and better response to favorable conditions with high grain yield (Bughdady, 2016). In Mali, sorghum cultivation through a mining agriculture coupled with several abiotic and biotic constraints, continues to record low productivity for about 1 t ha^{-1} (Annuaire Statistique, 2019). Among constraints hampering sorghum production, unsustainable management practices related to soil fertility problems (Bationo & Waswa, 2011; Tabo et al., 2011; Ajeigbe et al., 2018), issues of sowing dates due to climate variability (Marteau et al., 2011; Traore et al., 2014) and poor adoption rate of improved sorghum cultivars (Kelly et al., 2015; Sissoko et al., 2019) remain some critical constraints in sorghum production system in Mali. Studies of evaluating sorghum genotypes under management practices related to soil fertility and sowing dates issues in different agroecological zones in Mali have been addressed by Diancoumba et al. (2021) and Akinseye et al. (2023). But our study on the same issues has the originality of testing management practices among which the combined half doses of recommended organo-mineral fertilization. As smallholders have a poor purchasing capability to afford inputs for poor crops like sorghum, and millets, this low-cost practice applied at optimum sowing date could be an alternative management strategy to sustain sorghum production system in Mali. In this way, our study aims at determining the effects of different fertilizer types and sowing dates (intermediate and late sowing dates) on the yields (biomass and grain) and water use efficiency of grain yield of three improved sorghum variety in the Southern and the Northern parts of the Sudanian agroecological zone of Mali.

Materials and methods

The study was conducted at ICRISAT Samanko and IER N'Tarla research stations representing the southern and the northern parts of the Malian Sudanian agroecological zone. Three improved sorghum varieties were used including two medium maturing varieties (Pablo and Soubatimi) and one early maturing variety (Jakunbe). The trials were conducted in split-split plot design in 2021 and 2022 growing seasons. Treatments consisted of: (1) main factor: fertilizers strategies including the control, the recommended option (100 kg ha^{-1} DAP + 50 kg ha^{-1} Urea), the organic amendment (5000 kg ha^{-1} cow dung) and the combined option (50 kg ha^{-1} DAP +25 kg ha^{-1} Urea + 2500 kg ha^{-1} cow dung), (2) subfactor: 2 sowing dates (SWD1: medium and SWD2: late sowings times) with 3 weeks interval, (3) sub-sub factor: 3 sorghum varieties (Soubatimi, Jakunbe and Pablo). Aboveground biomass at harvest (AbgBHT), grain yield and crop water use efficiency (WUE) were the agronomic parameters evaluated.

Results and discussion

During the two cropping seasons at Samanko where significant differences were found among sowing dates, the results revealed that SWD1 produced higher stover (4091 and 5372 kg ha^{-1} in 2021 and 2022, respectively) and grain (1485 and 2065 kg ha^{-1} in 2021 and 2022, respectively) yields, as well as improved Water Use Efficiency (WUE) for grain yield (3.07 and 4.67 kg ha^{-1} mm^{-1} in 2021 and 2022, respectively) compared to SWD2 [(2484 and 4179 kg ha^{-1} in 2021 and 2022, respectively), (1362 and 1384 kg ha^{-1} in 2021 and 2022, respectively) (2.97 and 3.69 kg ha^{-1} mm^{-1} in 2021 and 2022, respectively)] (Tables 1 and 2). SWD1 stover and grain yields outperformed those of SWD2 by a maximal increase of 65% (2021 season) and 30% (2022 season) for biomass and grain, respectively. Those results are in conformity with the findings of Nwajei (2023), Wang et al. (2019) and Hadebe et al. (2017) for biomass, grain yield and WUE respectively. The organo-mineral fertilization (F4) outperformed all the other fertilization strategies for all the studied parameters (biomass and grain yields and WUE) (Tables 1 and 2). At Samanko, the F4 grain yield of 1779 and 2219 kg ha^{-1} in 2021 and 2022 cropping seasons respectively were at 169 and 109% greater than in the control F1. Similar results were reported by Bayu et al. (2006), Akinseye et al. (2023) and Singh et al. (2023) for biomass, grain yield and WUE respectively. At Samanko where significant difference was noted among varieties, Pablo registered the highest grain yield (1765 and 2740 kg ha-^{1} in 2021 and 2022 seasons, respectively) ahead Soubatmi (1363 and 1625 kg ha^{-1} in 2021 and 2022 seasons, respectively) and Jakunbe (960 and 990 kg ha^{-1} in 2021 and 2022 seasons, respectively) (Table 1). Likewise, Pablo was the variety with the best WUE to produce the greatest grain yield (Table 2). Our results agreed with those of Dembele et al. (2020) and Ajeigbe et al. (2018) for grain yield and WUE respectively.

Table 1: Fertilizer types, sowing dates and variety effects on biomass and grain yields at Samanko and N'Tarla sites

Agroecological zones / Sources of variation	Samanko (Southern Sudanian zone)				N'Tarla (Northern Sudanian zone)			
	AbgBHT (kg ha^{-1})		YIELD (kg ha^{-1})		AbgBHT (kg ha^{-1})		YIELD (kg ha^{-1})	
	2021	2022	2021	2022	2021	2022	2021	2022
Sowing dates (SWD)								
- SWD1	4091	5372	1485	2065	6105	5668	2305	2285
- SWD2	2484	4179	1362	1384	4257	4256	1696	2081
- Pr (>F)	<.001		0.003		NS		NS	
- LSD	642.3		325.1		867.2		330.1	
Fertilizer types (FRT)								
- F1	1904	2991	661	1061	4236	4297	1624	1858
- F2	3996	5176	1685	1797	5513	4690	2180	2156
- F3	3152	5268	1366	2023	5267	5418	2127	2421
- F4	4097	5668	1779	2219	5709	5442	2072	2298
- Pr (>F)	0.010		0.032		NS		NS	
- LSD	658.6		334.5		1529.3		368.9	
Varieties (VTY)								
- Jakunbe	2618	2787	960	990	2542	3002	726	983
- Pablo	4083	6795	1765	2740	4798	6830	2724	2632
- Soubatimi	3162	4745	1363	1625	6171	7085	2552	2935
- Pr (>F)	<.001		<.001		<.001		NS	
- LSD	552.2		328.2		851.8		338.4	
Interactions								
SWD*FRT	0.025		NS		NS		NS	
SWD*VTY	0.029		NS		NS		0.022	
FRT*VTY	NS		NS		NS		NS	
SWD*FRT*VTY	NS		NS		0.046*		NS	

Table 2: Fertilizer types, sowing dates and variety effects on grain water use efficiency at Samanko and N'Tarla sites

Agroecological zones / Sources of variation	Samanko (Southern Sudanian zone) WUE-Grain yield (kgha^{-1} mm^{-1})		N'Tarla (Northern Sudanian zone) WUE-Grain yield (kgha^{-1} mm^{-1})	
	2021	2022	2021	2022
Sowing dates (SWD)				
- SWD1	3.07	4.67	5.17	5.34
- SWD2	2.97	3.69	4.26	5.41
- Pr (>F)	0.042		NS	
- LSD	0.754		0.795	
Fertilizer types (FRT)				
- F1	1.39	2.30	3.67	4.43
- F2	3.72	4.20	5.10	5.26
- F3	3.01	4.88	5.06	6.10
- F4	3.96	5.32	5.04	5.73
- Pr (>F)	0.021		NS	
- LSD	0.797		0.928	
Varieties (VTY)				
- Jakunbe	2.41	2.68	1.95	2.72
- Pablo	3.83	6.15	6.45	6.33
- Soubatimi	3.69	3.83	5.75	7.09
- Pr (>F)	<.001		NS	
- LSD	0.771		0.843	
Interactions				
SWD*FRT	NS		NS	
SWD*VTY	NS		0.019	
FRT*VTY	NS		NS	
SWD*FRT*VTY	NS		NS	

Conclusion

In conclusion, we noted that in both zones, planting at intermediate sowing time (SWD1) (a window from the 20th of June to the first week of July) leads to considerable increase of yields (grain and biomass) and WUE contrary to plant at late sowing dates (period starting practically from the 10th of July up to the 25th). Among the fertilizer types, the organo-mineral fertilization (F4) made of the half dose of F2 and F3 (50 kg ha^{-1} of DAP + 25 kg ha^{-1} of Urea + 2500 Kg ha^{-1} of cow dung) outperformed the control plots F1 and the two national recommended fertilization rates including the sole inorganic fertilization F2 and the sole organic fertilization F3 for all the studied parameters (biomass and grain yields and WUE of grain yield). For grain yield, Pablo was the highest productive variety. For the study's agroecological zones, we recommend Pablo and Soubatimi for SWD1, and Jakunbe for SWD2, all with the organo-mineral fertilizers application.

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Modelling High-Resolution Soil Maps of Gombe State, North-Eastern Nigeria for Climate-Smart Agriculture With Sentinel 2A and In-Situ Data in Google Earth Engine.

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Abstract

Climate-Smart Agriculture (CSA) aims to improve agricultural productivity, increase resilience (adaption to climate change), and mitigate/remove greenhouse gas emissions. Satellite Remote Sensing (SRS) plays a vital role in Climate Smart Agriculture (CSA) by providing data and information that helps make informed decisions that are productive and sustainable for the environment. A major application of remote sensing in CSA is the provision of Soil Information Systems (SIS) or Digital Soil maps (DSM). The use of satellite remote sensing data to improve knowledge of local-scale and soil information systems has not been fully explored in Nigeria, particularly for Soil Science. This study uses high-resolution satellite data to map the spatial distribution of some soil fertility parameters. namely: Organic carbon, total N, available P, Ca and K for the 20,256 square kilometre land mass of the North Eastern State of Gombe, Nigeria. The African Soil Information Service (AfSIS) protocol was adopted in collecting soil samples at 0 - 20cm depth. The dry chemistry method involved the use of Near Infrared (NIR) Spectroscopy analytical method was used to analyse the 102 samples obtained from the study location. Data obtained were used as input sample training data and were divided into 70/30 for modelling and validation. The Random Forest Regression (RFR) algorithm was deployed in the modelling of the respective soil chemical properties. Results obtained showed that the linear regression models based on the Bare Soil Index (from the 10-meter sentinel 2A image spectral variable) produced excellent spatial distributions of the soil properties, with R^2 values of 0.66, 0.42, 0.52, 0.63 and 0.71 for organic carbon, total N, available P, Ca and K respectively. This study therefore implied that the 10-meter resolution Sentinel 2A data provided great potential to predict/produce the soil maps of Africa with high accuracy using the Google Earth Engine platform. The soil fertility information provided in the modelled DSM can serve as a game changer in the management and practices of Climate-smart agriculture for sustainable food security, system resilience, and adaptation.

Keywords: Satellite Remote Sensing, Google Earth Engine, Digital Soil Maps. Climate-Smart Agriculture.

Introduction

Climate-smart agriculture (CSA) is an integrative approach to landscape management. It aims to achieve sustainable agricultural productivity through increasing livelihood incomes, adaptation and resilience to climate change, and reducing or removing greenhouse gas emissions (Loboguerrero et al., 2019; Reddy, 2015; Saj, 2017). The significance of CSA increases as climate change presents a danger to global food security. A paradigm shift in landscape management is the introduction of CSA-enhancing technologies which increases the productivity of CSA, thus reducing the impacts of climate change. Digital soil mapping (DSM) is a cutting-edge tool allowing more accurate and effective soil management among the many technical innovations supporting CSA. The traditional soil survey methods are often time-consuming, expensive, and lack the necessary information needed for site-specific management decisions for large expanses of land other than the areas surveyed (Flynn, de Clercq, 2019; Van Ranst, 2010), resulting in a generalised approach to irrigation, tillage, and fertiliser application that may be ineffective and harmful to the environment.

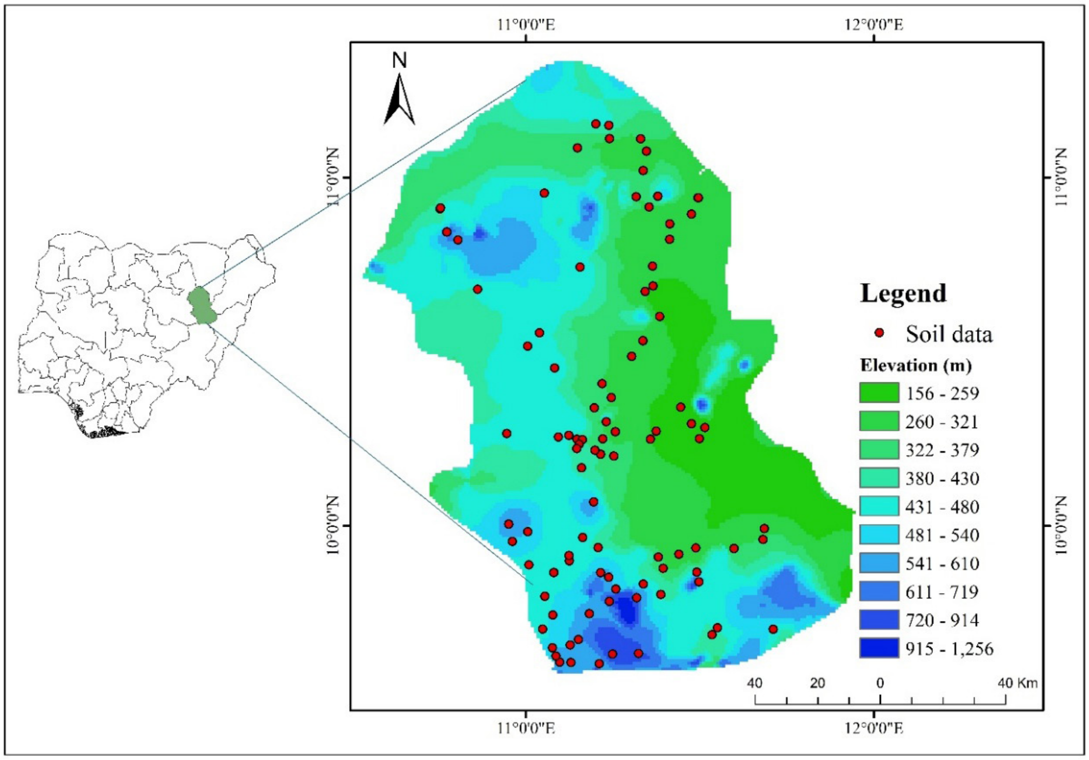
These limitations are circumvented by Digital soil maps (DSM). Digital soil mapping is used to produce low to high-resolution digital soil maps using cutting-edge technologies like remote sensing and geo-statistics with soil survey data. Digital soil maps represent the spatial distribution of different soil properties such as water-holding capacity, nutrient availability, and organic matter content (Folorunso et al., 2023; Tomislav et al., 2015; Lagacherie, 2008; López-Castañeda et al, 2022). It is an essential technique in soil research that produces detailed maps of the types and attributes of soil leveraging the use of satellite remote sensing, artificial intelligence/ machine learning algorithms and ancillary data. A notable progression in DSM involves the utilisation of satellite data, ranging from the low-resolution satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to the medium-resolution Landsat data, all from the United States Geological Survey (USGS). The European Union recently launched the Copernicus programme which birthed Sentinel-2A, a 10-meter multispectral high-resolution satellite data (Dewitte et al., 2012; Tomislav et al., 2015; Lagacherie, 2008; Xiao et al.,2020).

Sentinel-2A's multispectral data has been used to model the spatial distribution of various soil properties, such as organic carbon content, soil texture, moisture, and salinity (Tomislav et al., 2015; Van Ranst et al., 2010; Xiao et al., 2020). Machine learning algorithms such as Random Forest, Support Vector Machine, and spectral indices such as the Bare soil index, Normalized Difference Vegetation Index are commonly applied. Studies have shown that Sentinel-2A data can effectively estimate soil organic carbon and texture with reasonable accuracy, especially when combined with field sampling and ground truth data (Adeniyi et al., 2024; Chen et al., 2022; Flynn et al., 2019; Xiao et al., 2020). In most African countries information spatial information on fertility is either lacking or inadequate (Eswaran et al, 1997) and this has hindered the full upscaling of climate-smart agricultural practice (Flynn et al., 2019; Hengl et al., 2021; Van Ranst et al., 2010). The potential of using satellite remote sensing data to improve knowledge of local-scale and soil information systems has not been fully explored in Nigeria. This study uses high-resolution sentinel 2A satellite data to map the spatial distribution of some soil fertility parameters of the North Eastern State of Gombe, Nigeria.

Material and Methods

The study area.

Gombe state is in the Central part of northeastern Nigeria and covers an area of about 20,256 km^2. The state is located between latitudes 11°14'10.84"N, longitude 10°35'33.99"E, latitudes 9°32'57.23"N, and longitude 11°52'23.06"E and has a climatic rhythm that is largely determined by the Intertropical Discontinuity Zone (IDZ); transient, discontinuous zones where the tropical maritime and tropical continental air masses meet. Rainfall peaks in August/September and the precipitation drops sharply in October. The three wettest months are July, August and September. From the months of November to March, there is either no rain at all or the total monthly precipitation is less than 25.50mm, the lower limit of effective rainfall. Annual rainfall figures ranged from 850 mm to about 1000 mm. About ninety per cent of the rain falls between May and September, the wettest months being July and August.



The mean monthly temperatures in the state ranged between 30 and 36°C, with the hottest months being March/April and the coolest months being December/January, have the lowest temperature averaging 16°C (UBRDA, 2018). Annual mean temperature in Gombe State ranged between 25 – 28°C.

Figure 1: Elevation map of Gombe State-Nigeria with the soil sample locations

The spatial pattern of the mean annual temperature followed the rainfall distribution pattern. The Northern Eastern part of the state is hotter (26.9 – 28°C) than the north-western and southern parts (25.2 – 26.8°C).

Materials

The North Eastern State of Gombe, Nigeria, spans 20,256 square kilometres, and Figure 2 provides a model of the techniques used to create the Digital soil maps of this area. Apart from the soil survey and laboratory analysis of the macronutrients which were used as a covariate. Satellite image acquisition, pre-processing and modelling of the DSM with environmental covariates were performed within the Google Earth Engine (Google Earth Engine) interphase. The workflows are described below with the graphic model in Figure 2.

Soil survey and laboratory analysis

The African Soil Information Service (AfSIS) protocol was adopted for collecting soil samples at 0 - 20cm depth. The dry chemistry method involved the use of the Near Infrared (NIR) Spectroscopy analytical method. Near-infrared (NIR) spectroscopy is based on the absorption of electromagnetic (EM) radiation at wavelength in the range of 780 and 2500nm (12,500-4000 cm^{-1}, expressed as wavenumber). This method was used to determine these fertility parameters namely, Organic carbon, total N, available P, Ca, and K obtained from the study location.

Satellite remote sensing acquisition and processing

Sentinel-2A, launched in June 2015, carries a multispectral instrument (MSI) capable of capturing 13 spectral bands ranging from the visible to the shortwave infrared region. This wide range of spectral bands, along with its high spatial resolution (10m, 20m, and 60m), enables detailed analysis of land cover, vegetation, and soil properties. Sentinel 2A with less than 10% cloud was loaded into the Google Earth Interphase; atmospheric correction was applied to Sentinel-2A imagery to remove atmospheric effects. Topographic normalization was performed using the 10-meter digital elevation model of the study area. The Bare Soil Index (BSI) was extracted as feature extraction and used the index for modelling digital soil maps.

$$BSI = \frac{((RED+SWIR)-(NIR-BLUE))}{((RED+SWIR)+(NIR+BLUE))} \quad \text{.......... 1.}$$

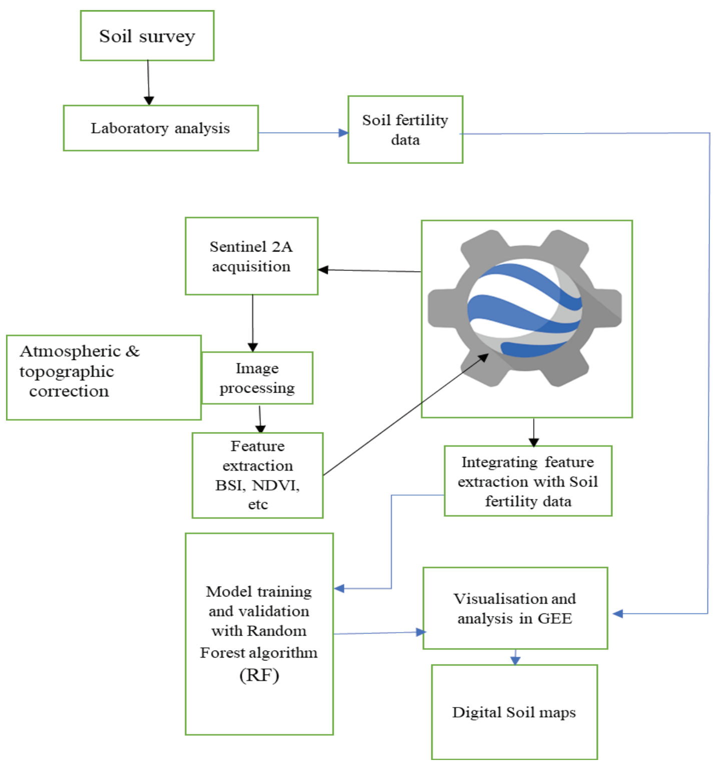


Figure 2. Model of soil showing digital soil map from field survey to modelling in Google Earth Engine.

Model Training and Validation:

Soil data obtained from the laboratory analysis were used as input sample training data and were divided into 70/30 for modelling and validation. The training data sets were used with the extracted Bare Soil Index to model the digital soil maps for the six soil chemical properties of the study area. Random Forest Regression (RFR) algorithm was deployed in the modelling of the respective soil chemical properties. Model performance was evaluated with the linear regression metric.

Results and Discussion.

The random forest algorithm was used to model and predict spatial distributions of these soil fertility parameters (Organic carbon, total Nitrogen, available Phosphorus, Calcium, and Potassium) with soil data from the field and the Bare Soil Index as a covariate data. The minimum and maximum values of the predicted soil nutrients (Table 1) were almost at par with the field soil samples.

Table 1. Minimum and maximum values of the predicted soil nutrients

Soil nutrient	Min	Max
Organic carbon	0	2
Total Nitrogen	0.01	0.09
Magnesium	0.1	0.7
Potassium	0	1
Calcium	-0.1	4
Average Phosphorus	-1	30

Results from the model validations were significant with the regression values ranging from 0.42 for Nitrogen to 0.71 for Potassium (Table 2).

Table 1. Model and regression results of chemical parameters of soil

	Derived model	R^2
Organic Carbon	y=0.2798x+0.3322	0.66
Total Nitrogen	y = 0.2508x + 0.0503	0.42
Available Phosphorus	y = 0.2169x + 1.2717	0.52
Calcium	y = 0.2169x + 1.2717	0.63
Potassium	y = 0.2981x + 0.3076	0.71
Magnesium	y = 0.3885x + 0.1463	0.61
CEC	y = 0.2266x + 2.9446	0.5954

Discussion

Gombe state which is the study site is located in the semi-arid region of Nigeria and typical of the semi-arid region are mostly denuded of vegetation or with sparse vegetation. The Bare Soil Index was used to model spatial distributions of six soil fertility parameters. Results of indicated the use of BSI as a covariate was able to model and predict the spatial distribution of the soil fertility parameters. In similar studies, BSI were used to model and predict the spatial distribution of soil organic carbon, Nitrogen, Calcium, available Phosphorus and Magnesium using Landsat 8 and Sentinel 2A respectively (Liu et al., 2022; Nguyen, 2021; Silvero et al., 2021). The use of Sentinel 2A multispectral satellite image with the 10-meter resolution for predicting the spatial distribution of soil chemical properties is a significant improvement over the previous digital soil maps with spatial resolutions ranging from 30 metres (Landsat) to 1 Km (MODIS). Model validation between the predicted and observed using the Bare Soil index shows was significant (Figure 2).

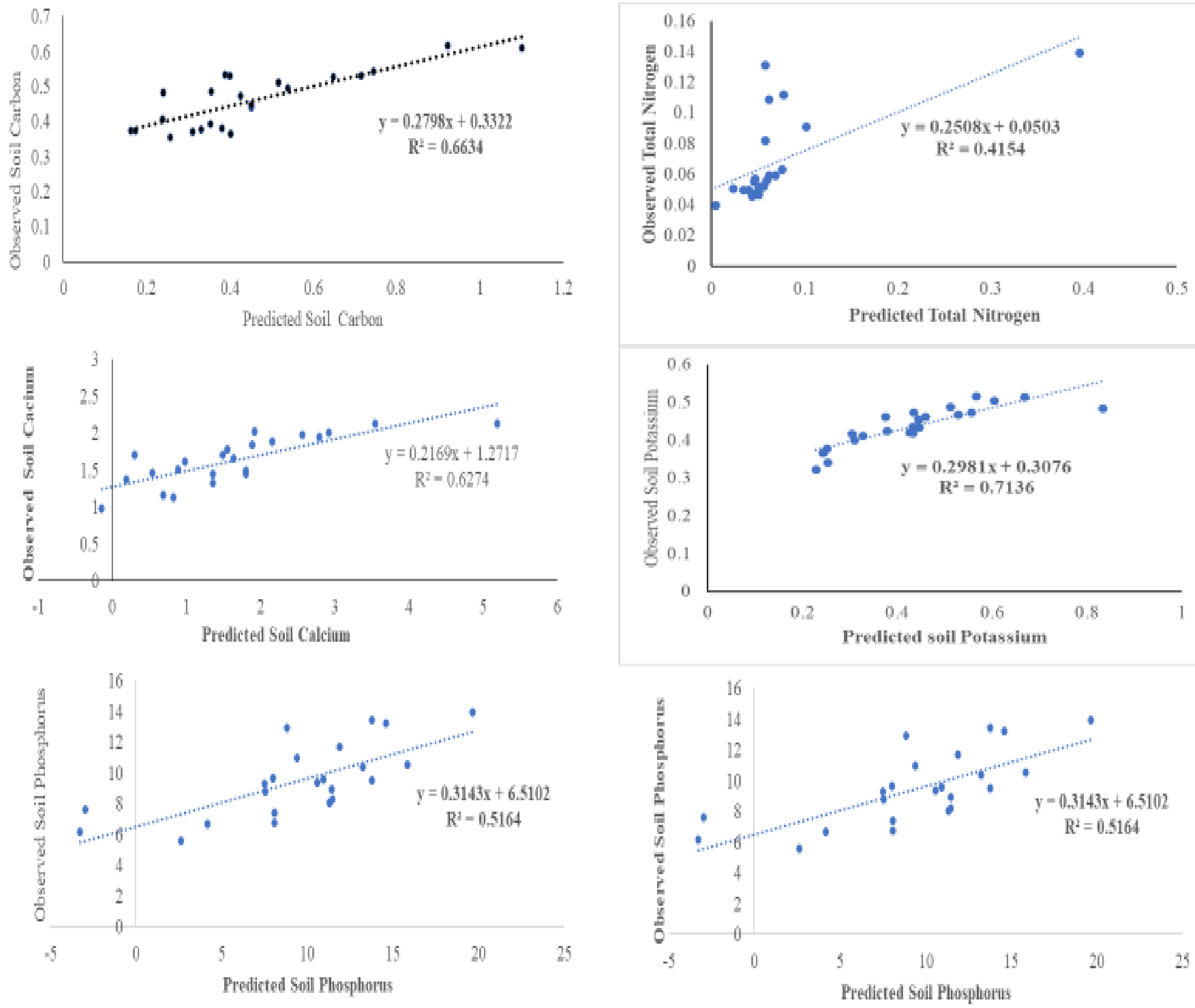


Figure 2. Graphs showing accuracy assessments for the six soil chemical parameters

Implications on Climate Smart Agriculture

Sub-Saharan Africa faces challenges in agricultural productivity due to factors like limited information on soil conditions. Digital soil mapping (DSM) emerges as a game-changer, offering a precise and efficient way to analyse soil characteristics. Digital soil mapping holds immense potential for transforming Sub-Saharan African agriculture. By providing detailed and up-to-date soil information, DSM can empower farmers, improve resource management, and enhance food security in the region. Addressing challenges related to accessibility and capacity building will be vital to ensure the widespread adoption and success of DSM.

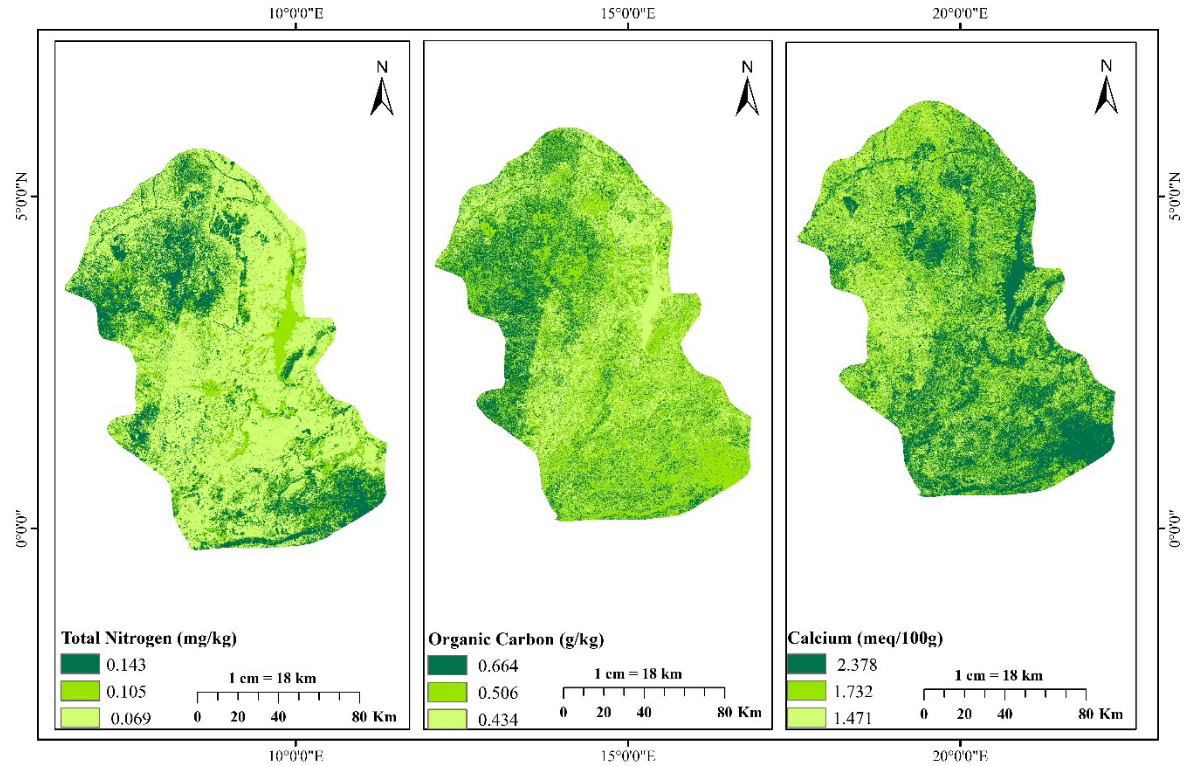


Figure 3. Digital Soil Maps (Nitrogen, Organic Carbon and Calcium) of Gombe State

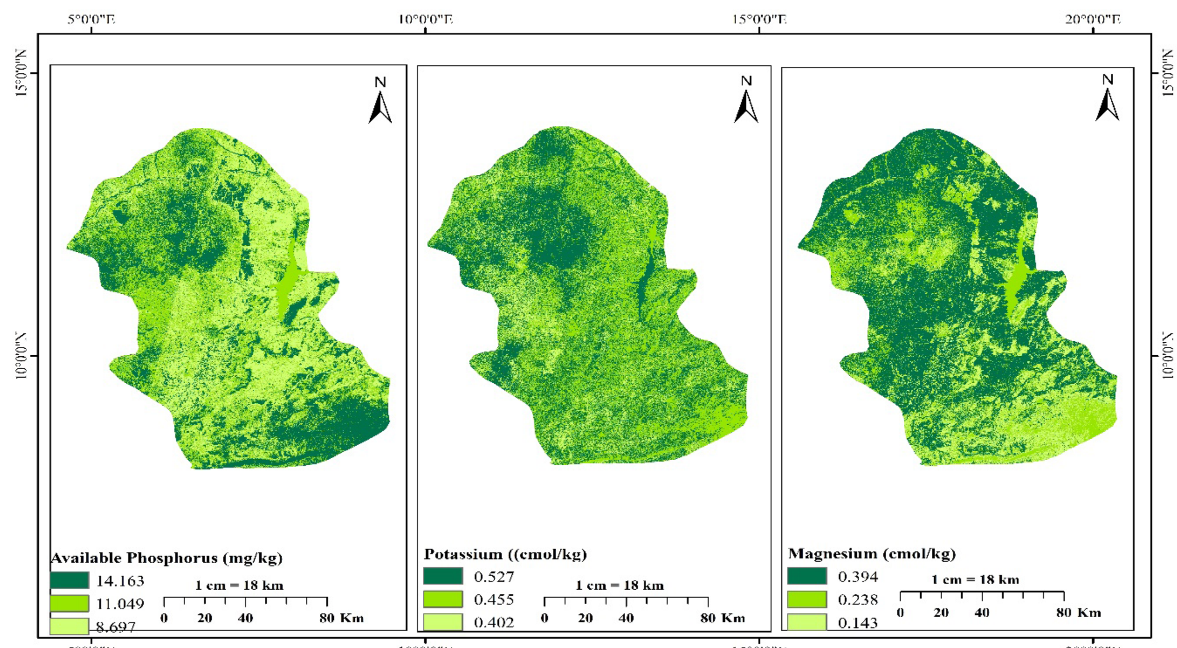


Figure 4. Digital Soil Maps (Available Phosphorus, Potassium and Magnesium) of Gombe State.

A major development in soil science, digital soil mapping enables accurate, scalable, and thorough solutions for environmental monitoring and soil management. Sentinel-2A has significantly advanced the field of Digital Soil Mapping by providing high-resolution, multispectral data that is freely accessible and highly versatile (Adeniyi et al., 2024; Chen et al., 2022; Flynn et al., 2019). Despite challenges, its integration with advanced analytical techniques and field data has enabled the creation of accurate and detailed soil maps, essential for sustainable land management and agricultural practices.

Conclusion

By leveraging GEE's cloud-based platform and freely available data, this approach offers a cost-effective and scalable solution for soil mapping, thereby supporting the development of climate-smart agricultural practices. Therefore, DSM's capacities and applications are expected to be greatly improved by interdisciplinary collaboration and the ongoing development of novel innovations and approaches in Nigeria and sub-Saharan Africa.

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Adoption of Climate-Smart Livestock Feed Technologies Among Rural Livestock Farmers in Niger

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Abstract

Seasonal scarcity of quality feed remains a major challenge for smallholder livestock farmers in the face of climate change. In particular, feed availability is the primary constraint on livestock production in agro-pastoral systems in Niger. Despite the introduction of various climate-smart feed technologies in the country, smallholder farmers have shown limited adoption rates. To address this issue, this study aimed to identify factors influencing the likelihood of utilizing climate-smart livestock feed technologies among smallholder livestock farmers in Niger to guide the design of context-specific approaches that ensure successful adoption of these technologies among agro-pastoral households. Data were collected through a household survey using a structured questionnaire. The survey was conducted in 2023 and involved 218 agro-pastoral households, stratified randomly selected based on gender. The study used an ordered probit model for modeling the level of the adoption of climate-smart livestock feed technologies, taking into account observed factors. The study revealed low utilization of climate-smart livestock feed technologies among livestock farmers. The majority of agro-pastoral households (76.6%) stated that they have never used any climate-smart livestock feed technologies. The findings show that 11.93% used them at a low level, 4.13% at a moderate level, while only 7.34% utilized climate-smart livestock feed technologies at a higher level. The findings suggested the positive impact of education level, membership of farmer groups, and ownership of small ruminant on enhancing the probability of using climate-smart livestock feed technologies. Households' geographical area was one of the determinant factors in using climate-smart livestock feed technologies. The use of climate-smart livestock feed technologies was also influenced by family size. The study provides valuable insights and guidance to inform strategies by the decision-makers to enhance the utilization of climate-smart livestock feed technologies among agro-pastoral households in Niger. These suggested strategies can help improve the resilience of livestock households, alleviate current issues of low livestock productivity, and contribute to enhancing household food security and nutrition among smallholder farmers' communities.

Key words: Adoption, climate smart, feed, technology, agro-pastoralist, smallholder farmer, Niger

Introduction

Livestock plays a crucial role in the livelihoods of farmers in Niger, with almost every rural household owning livestock. In fact, over 60 percent of the total population relies on livestock for their living [17]. The livestock population in Niger is estimated at 50.5 million, excluding poultry [18]. These animals provide meat, milk, and processed products for consumption, manure for crop production, traction power and income. In addition, livestock also holds social significance in certain communities.

While there is a projected growth in demand for animal products, the current production of livestock remains low. One of the main constraints to livestock production is the seasonal scarcity of high-quality feed resources [20,3]. Available animal feed resources consist of fodder from rangelands, crop residues, and agro-industrial by-products. Overgrazing has led to the depletion of soil fertility in rangelands, deterioration of its structure, increased erosion, and decreased biological activity. Additionally, population growth and increased cultivation of marginal lands and fallows have resulted in a significant decline in available grazing areas and a growing demand for crop residues and agro-industrial by-products [20]. Climate change further worsens the problems of feed availability by affecting the quantity and quality of feed resources [5]. Given the growing population and rising demand for animal protein, there is an urgent need to increase feed production and livestock productivity while addressing environmental issues and supporting circular economy concepts.

To address the problem of feed availability and improve the quality of available feeds, various climate-smart livestock feed technologies (CSLFTs) have been introduced to increase production and profitability [6]. These technologies include dual-purposed crop varieties, improved forage varieties, treatment of low-quality roughages to enhance their quality, chopping/grinding technology to enhance intake and reduce wastage, silage making, ration formulation, multi-nutrient blocks, and supplementation [16, 19, 4, 6, 1]. It has been proven that these technologies can increase the production of quality feed, reduce fodder waste, improve livestock production, and enhance the resilience of farmers to climate change. Furthermore, the utilization of these technologies may also reduce the environmental impact of livestock, create economic opportunities, and improve the resilience of the livestock system [6,8]. However, despite the introduction of these technologies and their potential impact on the livestock sector as well as on households' food and nutrition security, their utilization by smallholder farmers is currently very low. This study aims to understand the socio-economic factors behind the utilization of CSLFTs, to guide the design of context-specific approaches that ensure successful adoption of these technologies among agro-pastoral households (APHs).

Methodology

Study area

This study was conducted in Niger, a Sahelian country that is highly vulnerable to climate change. Niger is located in the West African Sahel region and is bordered by Libya, Chad, Nigeria, Benin, Burkina Faso, Mali, and Algeria (Figure 1). The country experiences arid and semi-arid conditions with variable rainfall patterns, primarily occurring in the short rainy season from June to September. Agricultural production in Niger is primarily rainfed and it is mainly subsistence in nature. Currently, less than 1% of the national crop land is irrigated. Smallholder farmers are therefore directly affected by the impacts of climate variability, which can reduce their food supply and increase the risk of hunger and poverty [25]. Limited adaptive capacity in the agricultural sector underlines the country's vulnerability to climate change [25].

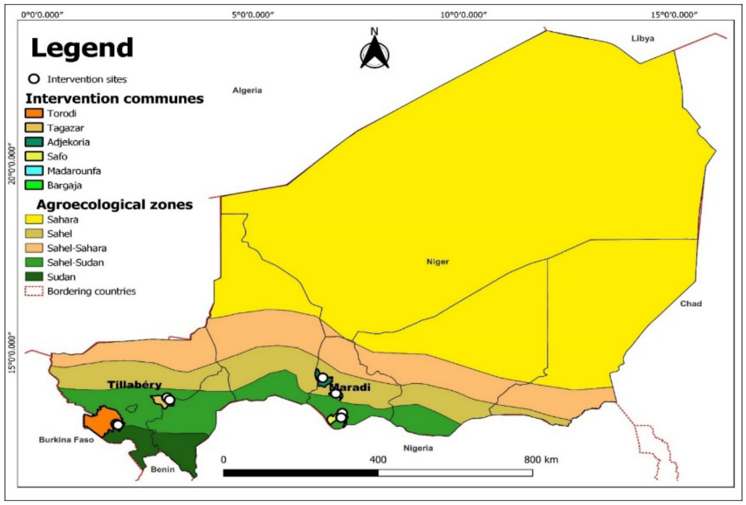

Figure 1. Presentation of the study area

The major cultivated crops in Niger are pearl millet (46%, covering 7 million hectares), sorghum (18%, covering 3 million hectares), and cowpea (32%, covering 5.7 million hectares) [18]. Livestock farming also plays a significant role in the agricultural system, with up to 85% of households in Niger owning cattle, sheep, goats, and other farm animals. Livestock contributes 13% to the country's GDP, and the average household owns 2.8 tropical livestock units (TLU) [26]. Mixed crop-livestock farming systems are widely practiced by farmers in Niger. Livestock accounts for approximately 10% of income for rural households in mixed systems and up to 43% of household income in pastoral zones. Despite these agricultural practices, agriculture in Niger is challenging, with climate change, limited opportunities for improving livelihoods, and a lack of access to or support for adapting to new technologies being the major constraints faced by existing farmers.

Climate -smart livestock feed technologies evaluated

The following climate-smart livestock feed technologies were evaluated in this study:

1. Improved multi-purpose cultivars (food-feed cultivars): The technology is about using improved new multi-purpose cultivars of legumes and cereals for improving availability and productivity of feeds. It addresses the critical need for more efficient and sustainable feed production, ultimately supporting improved livestock health and productivity.
2. Improved forage cultivars: The technology is about the introduction of varieties of fodder crops such annual legumes, short-lived perennial legumes and perennial grasses to increase the availability of high-quality animal feeds
3. Chopping (reducing particle size of crop residues): The technology is designed to enhance feed efficiency and minimize wastage. By finely chopping crop residues, the technology increases the palatability and intake of these residues by livestock, ensuring that more of the available feed is consumed rather than wasted. This practice not only optimizes the utilization of agricultural by-products but also supports sustainable livestock management by providing a more consistent and digestible feed source. Implementing this technology can lead to improved feed efficiency, better animal nutrition, and reduced feed costs for farmers.
4. Feed rations packages, urea treatment of crop residues: The technology is about formulating balanced rations based on local available feeds.
5. Silage making technology: Silage making technology is a method focused on enhancing the conservation of forage, particularly crop residues, to ensure a reliable and nutritious feed supply for livestock. This technology involves fermenting and storing green forage in anaerobic conditions, preserving its nutritional value, improving its quality, and making it more palatable and

easily digestible for animals. By converting crop residues into high-quality silage, this technique not only extends the shelf life of forage but also supports year-round feed availability, contributing to better livestock health and productivity. Implementing silage making technology helps farmers efficiently utilize available resources, reducing feed shortages and enhancing overall agricultural sustainability.

Data collection

Data were collected through a household survey using a structured questionnaire. The questionnaire was designed, pre-tested, and refined by a team of researchers. Six field enumerators collected the data. A two-day training workshop was organized for the enumerators to build their capacity. The survey, conducted in 2023, involved 218 agro-pastoral households in the Maradi and Tillabéri regions. Stratified random sampling based on gender was used to select households to be surveyed in each community. Data collection was facilitated by tablets with ODK software. The survey gathered information on socio-economic characteristics and utilization of CSLFTs.

Data analysis

Data cleaning and analysis were conducted using Microsoft Excel and STATA version 14. Descriptive statistics were employed to analyze the interviewees' level of adoption of CSLFTs. This study used an ordered probit model to model the level of the adoption of CSLFTs, taking into account observed factors. In this study, nine potential explanatory variables that are believed to influence the adoption of CSLFTs among agro-pastoral households in the study area were identified. Table 1 presents these variables along with their descriptions.

Results and Discussion

Socio-economic characteristics of agro-pastoral households

The results on socio-economic characteristics of APHs in the study area are presented in Table 2. The results showed that the average age of the household head was 52.05 and 50.18 years, respectively in Maradi and Tillabéri, with no significant difference between the two regions. Results on the education level of the household heads showed that the majority of heads of household had no formal education. High illiteracy rate of agro-pastoralists has been reported in many studies in sub-Saharan Africa [15, 11, 12]. In the Sahel region of Burkina Faso, [15] reported illiteracy rate of 41% among agro-pastoralists. Agro-pastoral household size was significantly higher in Maradi compared to household size in Tillabéri ($P<0.05$).

Land and livestock are important assets of APHs in the study area. On average, a household owned 3.88 ha. The average land size owned by APHs varied significantly between the two study sites and between type of APH. Male-headed households had larger land size compared to female-headed households. In term of cattle ownership, 43.90 % and 51.95 % households, respectively in Maradi and Tillabéri, responded owning cattle. Small ruminants were owned by 87.86 % and 84.62% agro-pastoral households, respectively in both regions. The average number of ruminant livestock kept by APHs were 1.19 TLU in Maradi and 1.76 Tillabéri with significant difference between regions. The results showed that the practice of agro-forestry was common among agro-pastoral households in the study area, especially in Maradi. The average number of trees on the farm was 75.97 trees in Maradi and 21.90 trees in Tillabéri, with significant difference between the two regions.

Concerning institutional factors, the findings indicate that 46.36 % and 48.72 % agro-pastoral households in Maradi and Tillabéri, respectively had at least a household 'member who was a member of farmer's group or association. This proportion is low compared to the proportion reported in other studies in the Sahel [15]. The mean annual household income from livestock was

41 850 CFA and 64 027 CFA whereas that from crop sale (farm income) was about 117 391 CFA and 66 267 CFA, respectively in Maradi and Tillabéri. Main source of income in APHs was from nonfarm works (rural exodus and remittance) (Figure 2).

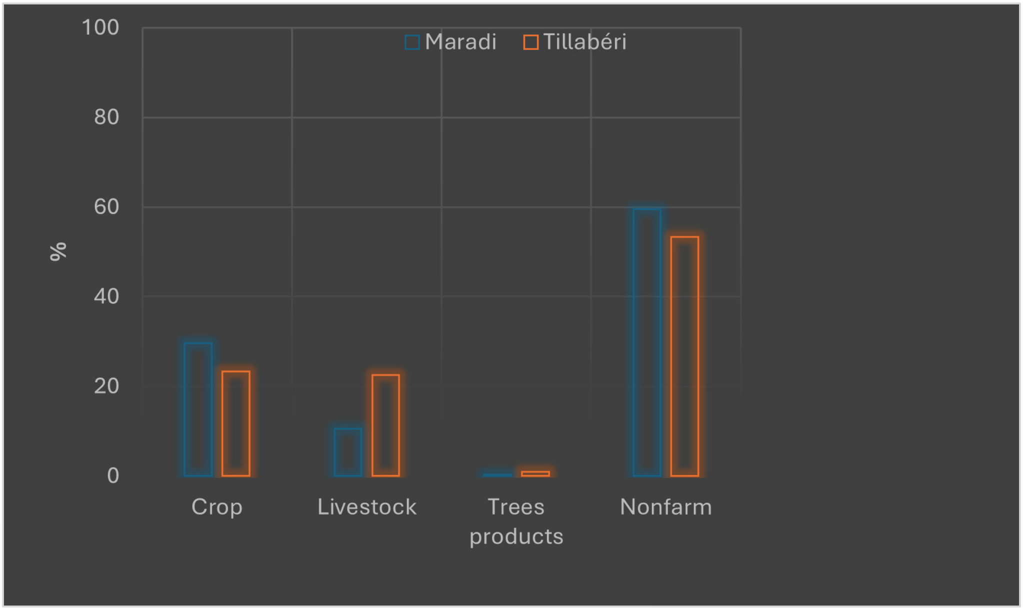

Figure 2. Major sources of annual household income in the study area.

Adoption of Climate-Smart Livestock Feed technologies

The level of adoption of CSLFTs in the study area was very low. In fact, the majority of agro-pastoral households (76.6%) stated that they had never used any CSLFTs. The findings show that 11.93% used them at a low level, 4.13% at a moderate level, while only 7.34% utilized CSLFTs at a higher level (Figure 3). Most respondents stated that they were not aware of these technologies, which explains the low level of adoption. In fact, awareness of agricultural technologies was listed as a factor that encourages adoption [14]. [10] also argues that the low adoption of agricultural technologies can be attributed to a lack of awareness among a significant portion of the population, especially when the technology is relatively new. The low adoption of agricultural technology has been reported in many other studies [24, 22, 23]. [24] concluded that forage adoption has been relatively poor across all tropical farming systems, despite 50 years of investment in forage research in the tropics.

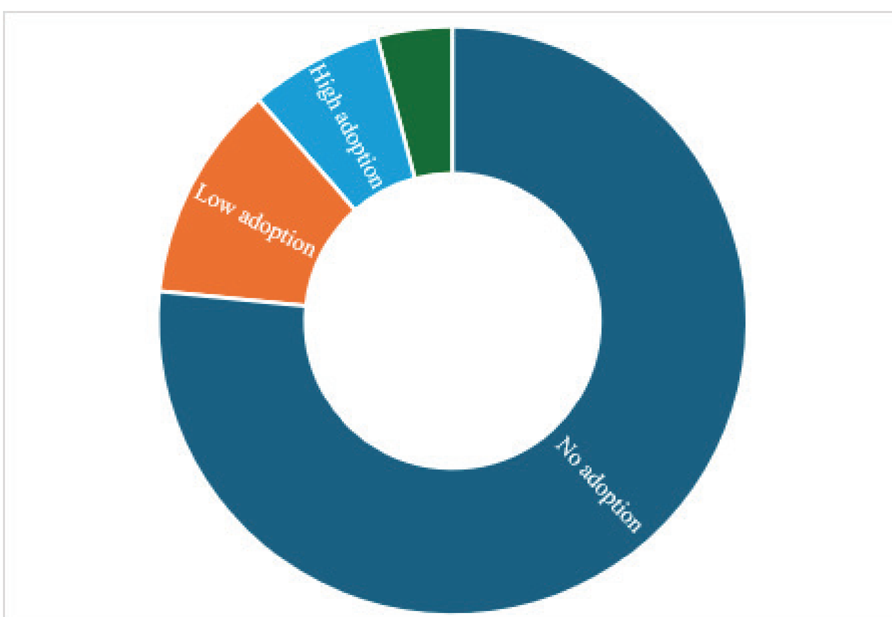

Figure 3. Level of adoption of climate-smart livestock feed technologies among agro-pastoral households.

Understanding the factors influencing the adoption of Climate-Smart Livestock Feed Technologies among agro-pastoral households

The overall model was statistically significant, with an overall percentage of correct predictions of approximately 83%. The p-value, computed from the Chi-square distribution with nine degrees of freedom (d.f), is 0.000. The results of the regression models indicate that the adoption level of CSLFTs was influenced by various factors at different levels of significance. This finding aligns with previous studies by [2, 7, 9, 23]. Table 3 displays six explanatory variables that were found to be significant at the 1% and 10% levels. Specifically, geographical area, age of household head, education level, membership in a farmer's group, household size, and ownership of small ruminants were identified as factors that were likely to influence the adoption level of CSLFTs among APHs.

Households in Maradi were more likely to use CSLFTs, possibly because of the available feed market opportunities. According to [7, 16] market access has been identified as an important factor influencing the adoption of improved technologies. Additionally, the adoption of CSLFTs increases when the household head has a higher level of education. This result is in line with previous studies that highlight the positive influence of education on technology adoption in agriculture [21].

The results of regression analysis also indicate that the level of adoption of climate-smart livestock feed technologies increased when household members were part of a farm group. Social membership or participation in farmers' group platforms has been found to be crucial for individual learning and experimentation, and it plays a significant role in the adoption process, leading to successful outcomes in relation to the technology being considered [13, 27].

Moreover, the variable age was statistically significant and positively affected the adoption of climate smart livestock feed technologies. This implies that the level of CSLFTs increases when the household head is older. This might be explained by the fact that older household heads often possess extensive experience and deep-rooted knowledge of local farming practices, enabling them to better understand the potential benefits and practical applications of new technologies. Their established social networks and community influence can also facilitate information dissemination and collective adoption efforts. Additionally, older farmers may have greater access to financial resources, land, and credit, allowing them to invest in advanced agricultural technologies.

In contrast, small households were more likely to adopt climate-smart livestock feed technologies. This may be attributed to the fact that, with fewer members, these households can prioritize their limited resources toward adopting and maintaining new technologies, thus ensuring proper and consistent use. Additionally, decision-making processes are often quicker and more straightforward in smaller households, which facilitates the faster adoption of innovative practices. Overall, the efficient resource management and streamlined decision-making of smaller households make them more agile and responsive to adopting improved livestock feed technologies.

Lastly, ownership of small ruminants has a positive impact on the adoption of climate-smart livestock feed technologies. This means that households that own goats and sheep are more likely to use CSLFTs [16]. These small ruminants offer a significant source of income and are easier to manage and more cost-effective than larger livestock, which provides an incentive to adopt climate-smart feed technologies. Furthermore, their ability to adapt to harsh climatic conditions encourages owners to adopt practices that enhance resilience and productivity. Additionally, the lower risk associated with experimenting on small ruminants allows for easier implementation and testing of new feed technologies.

Conclusion and Recommendations for Development

The study demonstrates that geographical area, education level, and membership in farmer groups have a significant positive influence on the likelihood of agro-pastoralists using climate-smart livestock feed technologies. Therefore, to enhance the adoption of these technologies among agro-pastoralists in Niger, it is recommended to employ participatory approaches that promote farmer engagement and increase awareness of these technologies. These approaches should involve partnering with champions to raise awareness, strengthening farmers' organizations, and enhancing the skills of agro-pastoralists.

Acknowledgement

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Table 1. Definitions of variables used in the ordered probit model

Description of variables	Type of measures
Adoption of CSLFTs	0=No adoption, 1=Low adoption, 2=Moderate adoption, 3= High adoption)
Independent variables	
Households' geographical area	Maradi/ Tillabéri
Age of the household head	Years
Member of farmer' organization	Yes/no
Education level	0 if no education 1 if adult education 2 if koranic education 3 if primary education is not completed 4 if primary education is completed 5 if secondary education
Ownership of cattle	Yes/no
Ownership of small ruminant	Yes/no
Land size owned by household	Cultivated area in ha
Households size	Number
Number of trees owned	Number

CSLFTs: Climate-Smart livestock feed technologies. No adoption: has never utilized any technology; Low adoption: uses one technology, but not regularly; Moderate adoption: uses two technologies from time to time; High adoption: uses two, three or more technologies on a regular basis.

Table 2. The socio-economic characteristics of agro-pastoral households in the study sites

Variables	Maradi	Tillabéri	Overall
Gender of the household head (%)			
Male headed HHs	80.71	73.08	78
Female headed HHs	19.29	26.92	22

Age of household head (years)	52.05±0.99[a]	50.18±1.47[a]	51.39±0.83
Education level of household head (%)			
No formal education	31.5	70.5	45.4
Koranic education	40	14.1	30.7
Adult education	5.00	2.56	4.1
Primary level education (not completed)	11.43	5.13	9.2
Primary level education (completed)	5.00	2.56	4.1
Secondary education	5.71	5.13	5.5
Post-secondary education	1.43	0	0.9
Household size (mean ±s.e)	14.66±0.63[a]	9.23±0.49[b]	12.72±0.47
Average number of children in school			
Male	1.96±0.15[a]	1.44±0.13[a]	1.77±0.11
Female	1.42±0.11[a]	1.46±0.11[a]	1.44±0.08
Total	3.38±0.22[a]	2.90±0.21[a]	3.21±0.16
Farmers' organization membership (%)	46.36	48.72	47.20
Ruminant livestock species kept (%)			
% of HH that owned Cattle	43.90	51.95	46.8
% of HH that owned small ruminants	87.86	84.62	86.74
HHs that owned sheep	44.85	67.95	53.00
HHs that owned goats	80.65	56.41	72.00
% of HH that owned Donkey	5.1	32.1	15.00
% of HH that owned Chicken	63.5	66.7	64.70
Total Number of ruminant livestock (TLU)	1.19±0.10[a]	1.76±0.26[b]	1.39±0.11
Average number of cattle (heads)	0.64±0.07[a]	1.30±0.23[b]	1.25±0.14
Average number of Small Ruminant (heads)	5.52±0.50[a]	4.62±0.56[a]	5.20±0.38
Total land size per household (ha)	4.39±0.33[a]	2.96±0.22[b]	3.88±0.23
Average land size owned by men/HH (ha)	4.68±0.39[a]	3.09±0.29[b]	4.15±0.29
Average land size owned by women/HH (ha)	3.8±0.45[a]	2.61±0.20[b]	2.93±0.27
Average number of trees on the farm (Agro forestry)	75.97±6.02[a]	21.90±2.00[b]	51.62±4.31
Annual household income in CFA	396 092±52827[a]	284 814±39789[b]	357274±37208
Appreciation of HH well-being status (%)			
Not satisfying	5.00	14.10	8.26
Satisfying	92.14	85.90	89.91
Very satisfying	2.86	0	1.83

HH: household; Livestock conversion unit: 1 cattle=0.7 TLU; 1 sheep/goat=0.1TLU; 1 USD=600 CFA. Values for a given variable on the same row with different superscripts are significantly different at P<0.05.

Table 3. Results of 'ordered probit' regression model of the adoption of CSLFTs among agro-pastoral households in Niger

Independent variable	Adoption of CSLFTs (No adoption, Low adoption, Moderate adoption, High adoption)	
	Coef.	S. E
Region (Maradi)	2.06***	0.81
Age of household head	0.03*	0.02
Education level of household head	0.87***	0.20
Membership in Farmer' organization	1.23***	0.41
Household size	-0.06*	0.03
Land size	0.02	0.06
Ownership of cattle	0.41	0.39
Ownership of small ruminant	1.49*	0.83
Number of trees in the farm	0.01	0.00
/cut1	8.47	1.67
/cut2	9.69	1.71
/cut3	10.32	1.74

*Number of observations= 218; the LR Chi-square test value = 83.16 (p= 0.0000); The Pseudo R2= 0.2442. *** Significant at the 1 % level, ** significant at the 5 % level, * significant at the 10 % level.*

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The Extent of Milk Losses in Rain and Dry Seasons Along The Milk Value Chain in Tanzania

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Abstract

Despite the Tanzanian government's policies, strategies and programmes which aim to ensure a stable market for milk and milk products in order to minimise losses, little is known about the current situation of the extent of post-harvest milk losses in the country. The above necessitated a study to determine the extent of milk losses at the various nodes of the milk value chain in both the dry and wet seasons and between regions. A cross-sectional research design was used to collect data in both the dry and wet seasons (June 2021 to September 2022) from milk producers, milk collectors, milk processors, retailers and hotels/restaurants/milk bars. Paired sample t-test results show statistically significant differences in milk losses between dry (7.8%) and wet (12.3%) seasons, $p = 0.000$ at the households; dry (3.5%) and wet (1.6%) seasons, $p = 0.006$ for mtindi/sour milk at the hotels/restaurants; dry (0.5%; 0.4%) and wet (0.02%; 0.05%) for fresh milk (UHT) and yoghurt respectively, $p < 0.05$ at the retailers; as well as Wilcoxon signed-rank test show significant differences in milk losses between dry (3%) and wet (6.8%) seasons, $p=0.014$ at the processors. In addition, a one-way ANOVA shows a statistically significant variations of milk losses across the studied regions (F-value = 16.967; $p=0.000$) of fresh milk at the households; $F = 3.3$, $p = 0.018$, $F = 4.2$, $p = 0.005$; $F = 6.8$, $p = 0.000$ for fresh milk, mtindi and yoghurt respectively at the retailers. Therefore, the Tanzanian government should create awareness of the milk value chain actors on the magnitude of the losses, the possible consequences and come up with policies and strategies or actions to minimise post-harvest milk losses along the whole milk value chain.

Keywords: Milk losses, post-harvest, value chain, wet and dry seasons, Tanzania

Introduction

Globally, the population is projected to increase from 7.7 billion people in 2019 to 9.7 billion people in 2050 with that of sub-Saharan Africa (SSA) projected to double from 1.1 billion people in 2019 to 2.1 billion in 2050 (UN, 2019). The projected population growth suggests an increase in demand for food, dairy products included. It is also forecasted by FAO (2019) that the growing population will lead to the increase in demand for agricultural products by 35-50% between the year 2012 and 2050. Therefore, the need for consorted efforts to minimize among others post-harvest milk losses so as to increase the supply and stability of dairy products as part of the general food security measures (FAO, 2011, 2009; FAO & LEI, 2015).

Further to the above, it is estimated that 13.8% of the food produced globally for human consumption is lost from the post-harvest stage before it reaches the retailers whereby 12% proportionate is for meat and other animal products (FAO, 2019). Other reports (FAO, 2011 & HLPE, 2014) show that one-third (1.3 billion tonnes/year) of the food produced globally for human consumption is lost or wasted (3% at production, 7% at post-harvest, 8% at processing, 12% at distribution and 17% at consumption level) due to spillage, spoilage and contamination. Post-harvest as defined by FAO (2018) refers to the period beginning after separation from the site of immediate production and ending when the food reaches its final use. Therefore, this study considers post-harvest to be the chain immediate after milking to the stage when the milk is ready for consumption. Despite the reported food losses, it is estimated that 820 million people globally are hungry (FAO *et al.*, 2019).

In SSA the extent of milk losses and waste per year is estimated to be 6% at the production level, 17% during post-harvest handling and 25% during storage (FAO, 2011). In East Africa, a study by Bingi and Tondel (2015) observed spoilage was a major risk for all milk actors in the dairy supply chain, with impacts on income loss and supply disruptions. In addition, post-harvest milk losses in the producing areas especially during the rainy seasons lead to most of the large urban centres relying on imported dairy products from outside East Africa particularly during the dry seasons. Moreover, post–harvest loss reduction initiatives are of paramount importance and these if captured by the various development strategies can be more effective than investing in additional production (ADB & FAO, 2011; Lipinski et al., 2013; Bechoff *et al.*, 2019; FAO, 2019; Principatoa *et al.*, 2019 & Sawicka, 2019). Moreover, literature (Nanda *et al.*, 2012; Aulakh *et al.*, 2013) shows that, reducing post-harvest losses or preserving what has been produced enhances the availability of food for domestic consumption. Similarly, FAO (2019) justified three gains of reducing food losses such as increased productivity and economic growth; improvement on food security and nutrition; and reduced environmental impacts by lowering pressure on land and water resources (reduced waste disposal and additional production as a substitutes of loss).

In Tanzania, a study by Lore et al. (2005) showed that, post-harvest milk losses are experienced in the small-scale informal dairy sector whereby, post-harvest milk losses at the farm level per year was quantified at 46.4 million litres (6.5%). In addition, milk losses are estimated to be 1.94% at collection centres; 2.2% at processing plants; and 1.32% at retailers (Lore *et al.*, 2005). Similarly, FAO (2004) as cited by ACF (2014) shows that post-harvest cumulative losses in Tanzania amount to about 59.5 million litres of milk each year with over 16% and 25% of total dairy production being lost during the dry and wet seasons respectively.

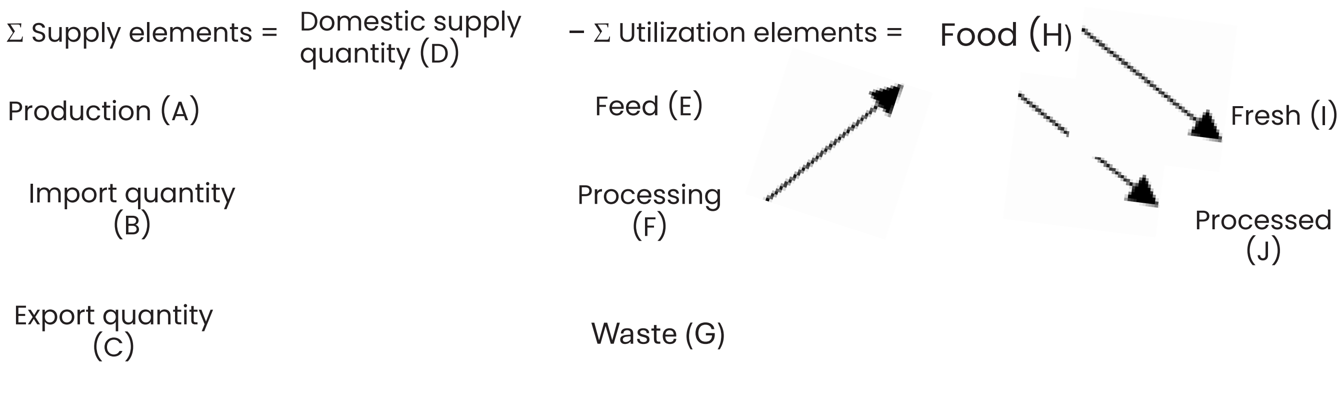
Tanzania has engaged in various policies, strategies and programmes aiming at contributing towards national food security through increased production, processing and by improving marketing infrastructure and marketing systems for livestock and livestock products; and insists on additional dairy investments and value addition through processing to ensure a stable market for fresh milk (URT, 2017a, 2011, 2010, 2006). Moreover, the Ministry of Livestock and Fisheries through Tanzania Dairy Board (TDB) and Private Sector Desk (PSD) have for a long time created an enabling environment and built capacity for milk collectors, dairy cooperative unions and milk processors with the latter two linked to financial institutions for easy access to loans for purchasing various facilities/equipment including milk cooling tanks (TDB, 2019, 2021 & URT, 2020). Based on the above, the annual milk production increased from 1.3 billion litres in the year 2005/06 (TDB, 2021) to 3.4 billion litres in 2021/22 (URT, 2022a). Similarly, the rate of milk consumption nationally increased from 35 litres per capita in 2005/06 to 55 litres per capita in 2020/21 (TDB, 2021), though the same is quite low when compared to the recommended 200 litres per capita as per FAO standards. Moreover, currently there are 105 milk processing plants/industries in Tanzania with an installation capacity of processing 872 700 litres of milk per day while the actual milk processing is 24.38% per day of its installed capacity (URT, 2022a). Therefore, suggesting existence of a milk supply deficit whereby post-harvest milk losses could be one of the reasons.

Despite the Tanzanian government's efforts to increase production, processing and marketing infrastructures for milk and milk products, little is known on the current situation of the extent of post-harvest milk losses in the country. For example, of the study by Lore *et al.* (2005) cited above was conducted almost 19 years ago. Therefore, the need for the current study to determine the extent of Tanzania's post-harvest milk losses at various milk supply chain actors in both dry and wet/rain seasons and among regions. Generally, the study was guided by two hypotheses i.e. there is no significant difference of milk losses between the dry and wet/rain seasons, and there is no significant difference of post-harvest milk losses between the studied regions.

The study aligns to Tanzania's policies and strategies that aim at increasing agricultural productivity and well-being of the farmers/producers. For example, the country's Agricultural Sector Development Programme Two (ASDP II) paragraph 220 among other things aims to reduce post-harvest losses by promoting and disseminating technologies that promote better handling and improved storage and preservation of food and food products including milk (URT, 2016). In addition, Tanzania's National Livestock Research Agenda (NLRA) 2020-2025 generally aims increasing communities' socio-economic benefits in relation to livestock, livestock products and by products. Furthermore, thematic area 4.1.5 aims at reducing post-harvest losses through increased products' shelf life, quality and biosafety (URT, 2019).The study is also in line with the United Nations Sustainable Development Goal (SDG) 12.3 which aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along the production and supply chains by the year 2030 (UN, 2015). Similarly, the African Union's Malabo Declaration Number III 3 (b) aims to halve crops, livestock and fisheries post-harvest losses by the year 2025 (AU, 2014). The findings from the study could be of great use to policy makers, academia, research institutions and other stakeholders interested in reducing post-harvest milk losses. Moreover, the study could provide basic useful information as an entry point for Tanzania's Ministry of Livestock and Fisheries to develop a "National Livestock Products Post-harvest Management Strategy" and "Country Program on Livestock Products Post-Harvest Losses (LPHL) Reduction".

Theoretical framework

The study was guided by the "Mass Flow of Milk Supply Model" developed by FAO (2011) which shows that, food losses takes place at every stage on the food supply chain especially at the farm production, postharvest handling and storage, processing and packaging, distribution and amount taken for consumption. The 'Mass flow milk supply model' (Figure 1) considers: Σ Supply elements (production, importation and exportation) = Domestic supply quantity – Σ utilization elements (feeding to calves, processing and waste) = Food (consumed as fresh or processed). The model regards animal feeds (milk used to feed calves) as food loss. However, according to literature (FAO, 2019, 2018) food used as animal feed should not be regarded as loss due to the fact that in the long run animals return to the food system. Therefore, milk loss in this study was calculated in each step of the food supply chain by considering proportional (in percent) of milk lost particularly at: Milking (households and Farms); at collection (milk collection centres - MCCs and hawkers/vendors); at Processing (processors); and at retailers and hotels/ restaurants/milk bars).



A+B-C=D-(E+F+G) = H = I + J

Figure 1: Mass flow model of milk supply chain

Source: Adapted from FAO (2011)

Conceptual Framework for the Study

The study's conceptual framework (Figure 2) shows the summarised four stages of the food supply value chain. The stages include production, collection, processing, and sales. Though, losses occur at each stage, they are of different forms and magnitude. The stages were modified from the work of Aulakh et al. (2013), and the losses from the mentioned stages were accounted at milking, collection, storage and transport key areas because each one was reported and recorded differently. Finally, the quantity handled versus quantity lost was reported in terms of litres or promotional loss (percent).

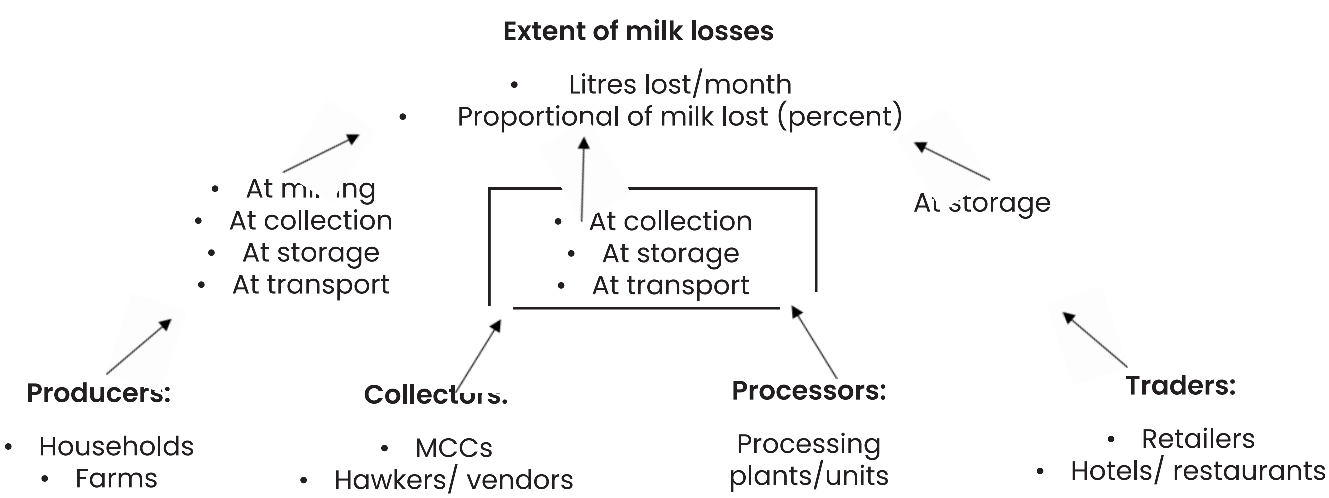


Figure 2: The conceptual framework for estimating post-harvest milk losses

Source: Modified from the work of Aulakh et al. (2013)

Methodology

Description of the study area

The study was conducted in five regions of Tanzania i.e., Dodoma representing the agro-pastoral and semi-arid production systems; Morogoro and Kagera representing the mixed rain-fed sub-humid and humid production systems; and Tanga and Iringa representing the mixed rain-fed highland production systems (Nell et al., 2014; URT, 2017b). In addition, about a third or above of the households in the selected regions are engaged in livestock production (64% in Dodoma, 37% in Tanga and Iringa and 30% in Morogoro and Kagera) (URT, 2017b). Further, the above regions were purposively selected based on the number of households keeping cattle (NBS, 2017); presence of cattle farms, milk collection centres (MCCs) and milk processing plants (TDB, 2021; URT, 2021) whereby regions that exceled in at least two or more of the criterion was sampled.

Research design

A cross-sectional research design was used to collect data in both the dry and wet seasons (June 2021 to September 2022). The research design was preferred because it allows determination of relationships between variables and can be done in a relatively short period of time while covering a large sample (Creswell, 2009; Gray, 2014; Kothari Garg, 2014). The study population involved milk producers (households and farms keeping cattle), milk collectors (collection centres and hawkers/vendors), milk processors, retailers and hotels/restaurants/ milk bars in the study areas.

Sampling procedure and sample size

The study used a multistage sampling technique to select the above-mentioned regions were considered as strata, therefore, the regions (stratum), districts, wards, villages and households keeping cattle were taken as the first, second, third, fourth and fifth sampling stages respectively. Further to the above, simple random sampling was used to select the respondents (household head or their representatives from households keeping cattle).

The sample size was determined using Cochran (1977) formula. It is estimated that 7.8 million Tanzanian households (65.3%) were involved in agricultural activities of which, 65% were involved in crop farming, 33% were involved in both crops and livestock keeping and 2% were involved in livestock keeping only (NBS, 2021). Similarly, Tanzania Livestock Sector Analysis 2016/17 – 2031/32 shows that, out of 4.6 million households owning livestock, about 35% households keep cattle (URT, 2017b). Therefore, using Equation 1, given by Cochran (1977), the study's sample was 388 respondents (household heads or their representatives) as shown below:

$$n = Z^2_{\alpha/2} P\,(1 - P)/e^2 \quad \text{(1)}$$

Where: n = sample size; $Z\alpha/2$ = the probability distribution with a level of significant α = 5%, "P" = proportion of the Tanzanian households keeping livestock (1-P) = proportion of Tanzanian households not keeping livestock and "e" = the level of marginal error.

Then calculation of the representative sample of the household heads was estimated considering the proportion of households involved in livestock keeping in Tanzania = 35%, a 95% confidence level or α = 0.05 and acceptable margin of error = 0.05 and non-response rate = 10%. Therefore, the required sample size was 388. n = (1.96x1.96x0.35x0.65)/0.0025/0.9 = 388.4284). But the researcher managed to interview 370 household heads or their representatives because, 18 respondents (3.6% non-response rate) missed the criteria to be interviewed in the second round/season, therefore were dropped in the process. In addition, 10% of MCCs, dairy farms, milk processors, hawkers/vendors, retailers, and hotels/restaurants/milk bars obtained from TDB and MLF reports and the regions or districts list were purposefully recruited for the study.

Data collection

Quantitative data for the post-harvest milk losses and average milk production/handling were collected using seven different questionnaires: the Households keeping cattle Questionnaire, the Large and Medium dairy farms Questionnaire, the Hawkers/Vendors Questionnaire, the Milk Collection Centres Questionnaire, Milk Processors Questionnaire, the Retailers Questionnaire and the Hotels/Restaurants/Milk Bars Questionnaire. The reason for using different questionnaires was the differences in model of operation and the nature of data to be gathered at the particular milk value chain actors. Then, the questions of each questionnaire were uploaded in a computer/mobile app (KoBoKollect) for easier and efficiency data collection. A total of 370 household heads or their representatives, 38 livestock farms managers, 35 in-charge of MCCs, 52 hawkers/vendors, 23 managers or in-charge of the processing units/plants, 51 retailers and 62 supervisors of hotels/ restaurants/milk bars interviewed.

In addition, key informant interviews (KIIs) were conducted to collect qualitative data. KIs included 5 Regional and 10 District Livestock and Fisheries Officers (RLFOs, DLFOs), Dairy Production Officer from TDB, Tanzania Livestock Research Institute (TALIRI), Dairy Nourish Africa's (DNA) Project Coordinator, Country representative of African Dairy Genetic Gains (ADGG) – Tanzania, and Tanga Dairy Cooperative Union (TDCU) Secretary. The discussions with KIs mainly based on the identifying the location of milk value chain actors, scale of milk production, losses and the causes, markets and marketing situation and strategies to be undertaken to reduce milk losses in their areas.

Data analysis

The Statistical Package for Social Sciences (SPSS) software (version 26) was used to check the data collected for accuracy where anomalies found were corrected accordingly. Data was analysed by running the paired sample t-test several times to measure proportional of mean difference of milk lost between the dry and rain/wet seasons in all the value chain actors nodes except for the processors where the Wilcoxon signed-rank test (non-parametric) was run because the sample size was small (less than 30 respondents), therefore not meeting the criteria of being normally distributed for parametric tests. In addition, one-way analysis of variance (ANOVA) was used to test the variation of milk losses across the five regions in all the milk value chain actors nodes except for the processors where Kruskal-Wallis test was used because the sample size was small (less than 30) therefore non-parametric test was opted. The differences between variables were considered statistically significant if the p-value was ≤ 0.05. Qualitative data collected from the KIs was analysed using content analysis.

Results and Discussions

Respondents demographic and socio-economic characteristics

The results in Table 1 show that over four-fifths (83%) of the households were headed by males while 17% were headed by females. The average household size in the area of study was 4.1, slightly below to what recorded during the 2022 Population and Housing Census for the United Republic of Tanzania which was 4.3 (URT, 2022b). Household size is an important indicator of the households economic status and individual wellbeing (URT, 2022b), which may also have implications on post-harvest milk losses at the household level. Also, sex of respondents (household heads) had implication on access to and control of milk handling facilities and participation in milk operations hence, leading to reducing post-harvest losses. A study by Zegeye & Teklehaymanot (2016) revealed that, milking practices is mostly practised by men while milk handling, processing and marketing primarily practised by women (wives). Therefore, understanding household characteristics particularly households head's sex is an important factor when looking for post-harvest milk losses. In addition, the majority (65.1%) of household heads were in age group of 36-60. Thus, suggesting the majority of the heads were in the economic active age group (URT, 2015) hence, able to participate in milk production, also age determines the competence and efficiency of milk handling operations, hence reduce or accelerate post-harvest losses (FAO, 2019). Table 1 further shows the majority (91.4%) of household heads had formal education (i.e. seven years of primary school education and above) suggesting the household heads are in a position to understand proper livestock husbandry practices for better milk production and handling. Moreover, about three-fifths (59.5%) of the household heads are engaged in livestock production as their main economic activity Thus, suggesting the economic status of the household has an implication on the access of milking handling facilities for milk operations (during milking, collection, storage and transport). Therefore, strategies for minimising post-harvest milk losses can have a substantial effect in uplifting the economic status of the households whose livelihood depends on livestock particularly, milk production. In addition, it is reported by FAO (2019) that, demographic characteristics of a household such as age, education and sex of the household head, and household size need to be considered when looking for post-harvest food losses as associated factors.

Table 1: Demographic and Socio-economic characteristics of the household head (n = 370)

Variable	Category	Total n(%)	Dodoma, n(%)	Iringa, n (%)	Kagera, n (%)	Morogoro, n (%)	Tanga, n (%)
Sex	Male	307(83)	61(82.4)	60(81.1)	64(86.5)	64(86.5)	58(78.4)
	Female	63(17)	13(17.6)	14(18.8)	10(13.5)	10(13.5)	16(21.6)
Age	25-35	28(7.6)	9(12.2)	2(2.7)	0(0)	7(9.5)	10(13.5)
	36-60	241(65.1)	39(52.7)	48(64.9)	51(68.9)	44(59.5)	59(79.7)
	>60	101(27.3)	26(35.1)	24(32.4)	23(31.1)	23(31.1)	5(6.8)
Education level	None	32(8.6)	12(16.2)	4(5.4)	2(2.7)	13(17.6)	1(1.4)
	Primary education	163(44.1)	38(51.4)	48(64.9)	41(55.4)	23(31.1)	13(17.6)
	Secondary	77(20.8)	12(16.2)	10(13.5)	10(13.5)	20(27)	25(33.8)
	Tertiary (Certificate Diploma)	62(16.8)	7(9.5)	3(4.1)	15(20.3)	8(10.8)	29(39.2)
	University	36(9.7)	5(6.8)	9(12.2)	6(8.1)	10(13.5)	6(8.1)
Marital status	Single	7(1.9)	5(6.8)	0(0)	0(0)	2(2.7)	0(0)
	Married	299(80.8)	59(79.7)	63(85.1)	65(87.8)	65(87.8)	47(63.5)
	Divorced	11(3)	0(0)	0(0)	1(1.4)	0(0)	10(13.5)
	Separated	13(3.5)	3(4.1)	2(2.7)	1(1.4)	0(0)	0(0)
	Cohabitating	1(0.3)	0(0)	1(0.4)	0(0)	0(0)	0(0)
	Widow/er	39(10.5)	7(9.50	8(10.8)	7(9.5)	7(9.5)	10(13.5)
Main occupation	Livestock production	220(59.5)	53(71.6)	48(64.9)	50(67.6)	46(62.2)	23(31.1)
	Crop production	61(16.5)	14(18.9)	18(24.3)	14(18.9)	15(20.3)	0(0)
	Government employees	37(10)	4(5.4)	1(1.4)	5(6.8)	4(5.4)	23(31.1)
	Private employees	21(5.7)	1(1.4)	1(1.4)	0(0)	6(8.1)	13(17.6)
	Self-employees & Casual labour (on and off farm)	31(8.4)	2(2.7)	6(8.2)	5(6.8)	3(4.1)	15(20.3)

***NB**: Figures outside the bracket are frequency and in brackets are percent*

***Age**: Median 52; Mean 53; Standard Deviation 11.92*

***Household size**: Median 4; Mean 4.1; Standard Deviation 1.81*

Extent of milk losses at the various nodes of the milk supply chain

The study findings (Table 2) show that, total fresh milk handled in supply chains (households, farms, MCCs, hawkers/vendors and processors) was high during the rainy season compared the dry season. High milk production during wet season is due to the availability of quality feed resources and adequate water supply while in dry season feeds especially pastures are of a poor quality and water is scarce making watering of cattle a challenge. In addition, the total milk losses by volume were also high in the rainy season compared to the dry season. The reported reasons by farmers were high milk supply during the rain/wet season to outflow the normal market available and the possibility of the whole milk produced to reach the processors is limited. In addition, handling and storage facilities are inadequate as well as difficulties some farmers face on transporting their milk from remote areas to the market during rainy season. The results suggest post-harvest milk losses vary by season and therefore, more needs to be done during the rainy season when there is a high production of milk compared to the dry season. The above results conform to what has been reported by Zegeye & Teklehaymanot (2016) that, shortage of animal feed resources (particularly in the dry season) cause low milk production. According to NBS (2003) as cited by Kurwijila et al. (2012) milk production during the dry season can be as low as 56% of that of the rainy/wet season due to variations in availability of feed/pastures. In addition, the results conform to Häsler et al. (2019) who revealed the existence of high milk outlets during rainy season and gradual decrease during the dry season. The result is supported by views of the KI who said:-

"Milk losses are more during the rainy season because milk production is high in the whole region to the extent of overflowing the market. During the dry season it is difficult to feel the situation but, during the rainy season livestock keepers especially in remote areas particularly where MCCs is hardly available face challenges of marketing their milk hence, milk losses" (RLFO Morogoro. 18/06/2021).

Table 2: Amount of fresh milk handled and lost (litres) per supply chain per month

Category	Households, n=370		Farms, n=38		MCCs, n=35		Vendors/ hawkers, n=52		Processors, n=23	
	Litres handled	Litres lost	Litres handled	Litres lost	Litres handled	Litres lost	Litres handled	Litres lost	Litres handled	Litres lost
Dry season	159,450	6,814	156,544	5,481	664,910	11,317	73,935	3,045	470,433	28,987
Rain season	238,212	16,683	210,938	10,651	1,078,910	24,913	94,730	4,330	652,941	86,242
At milking - Dry season	159,450	2,752	156,544	2,263	NA	NA	NA	NA	NA	NA
At milking - Rain season	238,212	8,174	210,938	2,934	NA	NA	NA	NA	NA	NA
At collection - Dry season	109,807	1,210	153,092	1,527	664,910	6,497	73,935	810	470,433	17,326
At collection - Rain season	232,524	2,835	172,792	3,505	1,078,910	13,956	94,730	1,553	652,941	22,448
At storage - Dry season	34,183.25	1,925	36,840	510	525,709	2,222	24,749	1,026	446,649	7,194
At storage - Rain season	76,403	2,979	48,002	1,614	863,359	8,486	18,221	1,137	617,589	11,469
At transport - Dry season	89,829	927	109,304	1,181	531,041	2,598	46,358	1,209	429,424	4,467
At transport - Rain season	213,367	2,695	122,928	2,598	902,478	2,471	33,259	1,640	59,9617	52,325

Source: Field data (2023)

Further to the above, the study results (Table 3) shows that, total fresh milk, mtindi (locally fermented/sour milk) and yoghurt lost in two supply chains (retailers and hotels/restaurants/milk bars) varies between rain and dry seasons.

Table 3: Amount of fresh milk and other milk products handled and lost (litres) per supply chain per month

Category	Hotel/restaurants (n=62)		Retails (n=51)	
	Litres handled	Litres lost	Litres handled	Litres lost
Fresh milk - Dry season	20 715	1 050	73 012.4	178.4
Fresh milk - Rain season	39 165	1 502.3	95 324	222
Mtindi - Dry season	7 920	765	40 075	151.6
Mtindi - Rain season	8 430	375	60 979	188.5
Yoghurt - Dry season	1 950	390	7 492	15
Yoghurt - Rain season	3 750	525	7 772	36.4

Determination of extent of milk losses in the dry and wet seasons using paired sample t-test

On determination of the extent of post-harvest milk losses, a paired sample t-test was run to measure the proportional of mean difference of milk losses. The results in Table 4 show a significant ($p \leq 0.01$) difference of fresh milk losses at the household level between the dry season (7.8%) and rainy season (12.3%) particularly, at milking the loss is 3.2% and 6.8% during the dry rainy seasons respectively; and at the transport to market level the loss is 1.6% and 2.5% in the dry and rainy seasons respectively and this was statistically significant at $p \leq 0.05$ level. In addition, the results in Table 4 show a significant ($p \leq 0.01$) difference of milk product losses (mtindi) at the Hotels/restaurants/milk bars at the rate of 3.5% and 1.6% during the dry season and rainy season respectively. Furthermore, the study shows a significant ($p \leq 0.05$) difference of milk product losses at the retailers level whereby the rate of fresh milk (Ultra-Heat Treatment - UHT) losses were higher during the dry season compared to the rainy season ($p \leq 0.05$), for yoghurt the rate of losses were higher in the rainy season and low in the dry season however, the difference was not statistically significant between the seasons. The results in Table 4 suggest that, households, hotels/restaurants/ milk bars and retailers' milk value chain experiences significant difference on milk losses between seasons (dry and wet/rain). However, for farms, MCCs and milk vendors/hawkers there were no significant difference of losses between the seasons. The above results conform to what was reported by Lore et al. (2005) that, milk losses are substantially high at the small-scale production (household) level. Similarly, a study by FAO (2004) as cited in ACF (2014) reported that, out of 59.5 million litres of milk lost per year in Tanzania, above 16% is during the dry season while 25% is during the rain/wet season. In addition, the study results conform to Amentae et al. (2015) who reported to have milk losses at the farmers, cooperatives (MCCs), retailers and processors. The result is supported by views of one KI who said: -

"Milk losses severally occur in wet season because milk supply is high, automatically the price goes down to the extent of discouraging some of milk value chain actors which makes some of the actors to be reluctant to sell their products at low price hence, milk spoilage or forced consumption, others feed to animals or offered to neighbours for free. Though, this goes hand by hand with lack of knowledge and skills of some actors on milk handling, markets and marketing" (DLFO Mufindi DC - Iringa. 25/03/2022).

Table 4: Paired Samples t-test results of post-harvest milk losses per supply chain

Actors	Groups compared	n	Mean milk losses (%)	t-value	df	Sig. (2-tailed)
Household	Dry season	370	7.788	-6.235	369	0.000***
	Rain season	370	12.331			
	At milking - Dry season	370	3.151	-9.214	369	0.000***
	At milking - Rain season	370	6.776			
	At collection - Dry season	285	3.324	-0.369	284	0.713
	At collection - Rain season	285	3.551			
	At storage - Dry season	169	7.460	1.645	168	0.102
	At storage - Rain season	169	5.143			
	At transport - Dry season	273	1.567	-2.18	272	0.03**
	At transport - Rain season	273	2.530			
Farms	Dry season	38	6.680	-1.766	37	0.086*
	Rain season	38	9.462			
	At milking - Dry season	38	2.070	-0.9	37	0.378
	At milking - Rain season	38	2.689			
	At collection - Dry season	38	1.881	-1.486	37	0.146
	At collection - Rain season	38	2.968			
	At storage - Dry season	38	1.030	0.171	37	0.865
	At storage - Rain season	38	0.960			
	At transport - Dry season	38	1.700	-1.133	37	0.265
	At transport - Rain season	38	2.845			
MCC	Dry season	35	2.627	-1.581	34	0.123
	Rain season	35	6.757			
	At collection - Dry season	35	1.640	-1.336	34	0.191
	At collection - Rain season	35	3.936			
	At storage - Dry season	35	0.511	-1.229	34	0.227
	At storage - Rain season	35	2.201			
	At transport - Dry season	35	0.477	-0.438	34	0.664
	At transport - Rain season	35	0.620			

vendors/hawkers	Dry season	52	5.785	-1.077	51	0.286
	Rain season	52	8.079			
	At collection - Dry season	52	1.986	-0.522	51	0.604
	At collection - Rain season	52	2.403			
	At storage - Dry season	52	1.748	-0.652	51	0.517
	At storage - Rain season	52	2.285			
	At transport - Dry season	52	2.050	-1.251	51	0.217
	At transport - Rain season	52	3.391			
Hotels/restau-rants/milk bars	Dry season - fresh milk	62	4.448	0.164	61	0.871
	Rain season - fresh milk	62	4.279			
	Dry season – mtindi	62	3.466	2.865	61	0.006***
	Rain season – mtindi	62	1.592			
	Dry season – yoghurt	62	0.599	0.534	61	0.595
	Rain season – yoghurt	62	0.419			
Retailers	Dry season - fresh milk (UHT)	51	0.463	2.48	50	0.017**
	Rain season - fresh milk (UHT)	51	0.434			
	Dry season - mtindi	51	0.556	-1.91	50	0.062*
	Rain season - mtindi	51	0.605			
	Dry season - yoghurt	51	0.021	-2.052	50	0.045**
	Rain season - yoghurt	51	0.049			

******, **, * are significance levels at 1%, 5%, and 10% respectively***

Further to the above, a study by Melesse et al. (2014) in Ethiopia found that, milk price is high during the high demand (in dry season when milk production is low) and price is low during the rain season when milk production is high, therefore post-harvest losses is prominent and forced milk consumption is obvious when production is high and price is low because milk actors fails to market all their produce. Based on the study results, the first hypothesis which stated that "there is no significant difference of milk losses between the dry and rain seasons" is rejected.

Furthermore, Wilcoxon signed-rank test was run to measure the extent of milk losses at the Processors. The results in Table 5 show a significant difference in milk losses at the processors between the dry and rainy seasons. The extent of milk losses (fresh milk) is 3% dry season and 6.8% rain season ($p<0.05$). The study by Lore et al. (2005) reported 1.5% milk spoilage at the processors due to electric failure in Tanzania. Similarly, Lore et al. (2005) and Minten et al. (2021) reported 2% milk losses at the processors in Ethiopia.

Table 5: Wilcoxon signed-rank test results of post-harvest milk losses per supply chain

	Groups compared	n	Mean milk losses (%)	T-statistic	z-value	Sig. (2-tailed)
Processors	Dry season	23	2.981	186	2.451	0.014**
	Rain season	23	6.761			
	At collection - Dry season	23	1.686	120	2.06	0.039**
	At collection - Rain season	23	3.129			
	At storage - Dry season	23	0.881	81	0.672	0.501
	At storage - Rain season	23	2.335			
	At transport - Dry season	23	0.414	44	0.392	0.695
	At transport - Rain season	23	1.297			

***, **, * are significance levels at 1%, 5%, and 10% respectively

Determination of extent of milk losses by regions

The extent of milk losses was also measured by one-way analysis of variance (ANOVA) to determine the variation of milk losses across the studied regions i.e., Dodoma, Iringa, Kagera, Morogoro and Tanga. Therefore, the F-Test was used to determine differences between the regions based on the proportional of post-harvest-milk losses along the milk supply chain. The F-test results (Table 6) show a significant difference ($p \leq 0.001$) in relation to household's fresh milk losses. The average post-harvest milk losses at the household level was 10.1%, whereby regions in descending order the losses are 20.7%, 13.5%, 6.7%, 5.6% and 3.8% for Dodoma, Morogoro, Iringa, Kagera and Tanga respectively. Mostly, respondents reported the loss to be caused by marketing challenges i.e., they have to travel long distances to market their products, also the absence or lack of nearby milk collection centre and/or milk processing plants to assure their collection and value addition through processing. Again, farmers reported that milk handling in most households was not properly done because some of them lack skills on milk handling procedures as a result milk losses occurs in most households. The above challenges were supported by DLFOs in Kondoa, Kyerwa, Mufindi, Mvomero DCs and Bukoba MC who reported that education of the milk value chain actors, enabling environments including infrastructures; milk handling facilities and market stability have justifiable effects on milk losses in their areas. According to Zegeye & Teklehaymanot (2016) milk handling facilities, storage, marketing and training of the milk value chain actors have implications on post-harvest milk losses. In addition, Table 6 shows significant difference at the retail level between milk losses of fresh milk (UHT) ($p<0.05$), mtindi and yoghurt ($p<0.01$) and regions. The total milk losses at retails are 0.45% for fresh milk (UHT), 0.59% for mtindi and 0.04% for yoghurt. For the case of MCCs though not statistically significant at the $p \leq 0.05$ level ($p=0.067$) but out of the 4.4% recorded total losses at MCCs, in Iringa was 19.1% followed by Morogoro (5%), Tanga (1%), and Kagera (0.4%). For example, Figure 3 represents some of the cases of milk spoilage observed during enquiry at Asari Farm milk collection point in Iringa Region which lead to a loss of thousand litres of milk due to inadequate supply of electricity. The only source of electricity at Asari Farm was generator (Appendix I) which seems to be expensive on its running because of high fuel consumption. Therefore, failure to get alternative source of energy at the farm, existence in milk business is questionable as asserted Asari Farm owner:

"In this wet season milk is plenty everywhere as a result the price in the market is very low which cannot compensate production costs. Sometimes, I feel forced to spill the milk or feed the calves with whole milk because the price offered at the market is too discouraging and the cost to cool milk at storage is high, the only source of energy to cool milk tank is generator which uses fuel and

I tried as much as I can to get alternative energy from Tanzania Electric Company (TANESCO) but not yet to succeed and the procedure is very complicated. Because of that I am not sure if I will exist in this business" (Asari Farm owner, Mufindi DC - Iringa. 25/03/2022).

Generally, the results conform to what was reported by (FAO, 2011) that, in SSA post-harvest losses is about 17%. Further, the above results conform to what Melesse et al. (2014) reported that, in Ethiopia post-harvest milk losses vary between different geographical locations. The losses is high in areas with poor milk handling infrastructures for collection and storage, lack of market, inadequate processing and poor transport to market (Zegeye and Teklehaymanot, 2016). Based on the study results the second hypothesis which stated that "there is no significant difference of milk losses between regions" is rejected.

Figure 3: About a thousand litres of milk spoiled due to inadequate electricity supply at Asari Farm collection point on 25.03.2022 in Itandula Ward, Mufindi DC, Iringa - Tanzania.

Table 6: Variation of Milk Losses by regions

	Regions	n	Mean milk losses (%)	Sum of squares between and within groups		df	Mean Square	F	Sig.
Households - Fresh milk	Dodoma	74	20.706	Between Groups	14517.429	4	3629.357	16.967	0.000***
	Iringa	74	6.731	Within Groups	78075.290	365	213.905		
	Kagera	74	5.596						
	Morogoro	74	13.533						
	Tanga	74	3.753						
	Total	370	10.064	Total	92592.719	369			

	Regions	n	Mean milk losses (%)	Sum of squares between and within groups		df	Mean Square	F	Sig.
Farms - Fresh milk	Dodoma	3	13.657	Between Groups	176.835	4	44.209	1.371	0.265
	Iringa	5	4.425	Within Groups	1063.919	33	32.240		
	Kagera	7	6.768						
	Moro-goro	17	8.543						
	Tanga	6	8.498						
	Total	38	8.071	Total	1240.754	37			
MCCs	Iringa	4	19.067	Between Groups	1100.472	3	366.824	2.631	0.067*
	Kagera	3	0.430	Within Groups	4321.469	31	139.402		
	Moro-goro	12	5.005						
	Tanga	16	0.969						
	Total	35	4.375	Total	5421.941	34			
Hawkers/vendors - Fresh milk	Dodoma	10	3.925	Between Groups	801.238	4	200.309	1.917	0.123
	Iringa	6	5.053	Within Groups	4911.536	47	104.501		
	Kagera	8	3.513						
	Moro-goro	13	13.605						
	Tanga	15	5.861						
	Total	52	6.970	Total	5712.774	51			
Hotels - Fresh milk	Dodoma	18	4.745	Between Groups	59.847	4	14.962	0.718	0.583
	Iringa	6	3.361	Within Groups	1187.033	57	20.825		
	Kagera	9	4.119						
	Moro-goro	12	5.836						
	Tanga	17	3.152						
	Total	62	4.294	Total	1246.881	61			
Hotels - mtindi	Dodoma	18	1.458	Between Groups	82.986	4	20.746	0.406	0.803
	Iringa	6	0.000	Within Groups	2912.101	57	51.089		
	Kagera	9	2.838						
	Moro-goro	12	3.542						
	Tanga	17	3.345						
	Total	62	2.438	Total	2995.087	61			

	Regions	n	Mean milk losses (%)	Sum of squares between and within groups		df	Mean Square	F	Sig.
Hotels - Yoghurt	Dodoma	18	0.000	Between Groups	23.268	4	5.817	0.583	0.676
	Iringa	6	0.000	Within Groups	568.455	57	9.973		
	Kagera	9	0.556						
	Moro-goro	12	0.000						
	Tanga	17	1.417						
	Total	62	0.469	Total	591.722	61			
Retailers - Fresh milk	Dodoma	10	0.435	Between Groups	8.690	4	2.173	3.341	0.018**
	Iringa	11	1.202	Within Groups	29.912	46	0.650		
	Kagera	7	0.207						
	Moro-goro	12	0.234						
	Tanga	11	0.081						
	Total	51	0.445	Total	38.603	50			
Retailers - Mtindi	Dodoma	10	1.518	Between Groups	11.831	4	2.958	4.210	0.005***
	Iringa	11	0.135	Within Groups	32.318	46	0.703		
	Kagera	7	0.459						
	Moro-goro	12	0.553						
	Tanga	11	0.320						
	Total	51	0.589	Total	44.150	50			
Retailers - Yoghurt	Dodoma	10	0.000	Between Groups	0.233	4	0.058	6.823	0.000***
	Iringa	11	0.000	Within Groups	0.393	46	0.009		
	Kagera	7	0.000						
	Moro-goro	12	0.000						
	Tanga	11	0.164						
	Total	51	0.035	Total	0.626	50			

******, **, * are significance levels at 1%, 5%, and 10% respectively***

Further to the above, Kruskal-Wallis test was run to determine differences in the extent of milk losses between regions at the processors level. The results show that total milk lost did not differ significantly across the studied five regions of Dodoma, Iringa, Kagera, Morogoro and Tanga [H (4) = 7.427, p = 0.115]. In addition, multiple comparisons across regions were not performed because the overall test did not show statistically significant differences across samples. Since the significance, i.e. p-value (0.115) for processors was greater than the critical value of $p \leq 0.05$, the study failed to reject the null hypothesis which stated that "Milk losses does not differ significantly between regions".

Conclusions and Recommendations

The study aimed to determine the extent of Tanzania's post-harvest milk losses at various milk supply chain actors in both dry and wet/rain seasons and among regions. Based on the study results it can be concluded that post-harvest milk losses vary between the rainy/wet and dry seasons as well as among the studied regions. Generally, the losses are high during the rainy season compared to losses recorded in dry season. The variation of losses between seasons is significant at the households, processors, hotels/restaurants/milk bars and at retails. Other supply chain the loss is not significant nonetheless, it is substantial for example milk lost at the farms and vendors/hawkers. In addition, at regions, the loss was significant at the households and retailers levels where, at the household level, milk losses were very high in Dodoma Region and low in Tanga Region while at the MCCs the losses were very high in Iringa and low in Kagera. Therefore, it is recommended that the Tanzanian government, through the Ministry of Livestock and Fisheries, should create awareness to the milk value chain actors on the magnitude of the losses and the possible consequences. In addition, the government of Tanzania should come up with policies and strategies or actions to minimize post-harvest milk losses along the whole milk value chain. By doing so, productivity and economic growth per value chain actors will increase; food security and nutrition per household and community level at large will improve; and pressure on production resources per value chain actors will be lowered.

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Optimizing the Effects of Additional Straw Returning on Soil Organic Carbon Components; Insights from a Chinese Long-Term Conservation Field Study

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Abstract

Since the return to straw management in conservation fields, it remains unknown the optimum quantity needed for good soil health and plant production. This study aims at highlighting the lessons from a study conducted on an existing long term-term conservation tillage field within the Gansu Province of China. Two main tillage types, conventional tillage with straw returns (TS) and no tillage with straw returns (NTS) with four different additional straw return treatment levels with spring wheat and field pea were used as test crops. NTS fields showed more sensitivity to treatment effect. NTS fields had significantly higher grain yield and soil organic carbon (SOC) content than TS fields with SOC ranging from 5.56 – 20.77 g kg^{-1}. No straw addition (NSA 0x) and low straw addition (LSA 1x) levels recorded higher yields in wheat fields whiles for pea fields, it was LSA 1x and medium straw addition (MSA 2x). The observed trend in terms of increasing SOC content among the straw addition treatments was LSA 1x > NSA 0x > MSA 2x > high straw addition (HSA 3x). Highest accumulated SOC stocks was observed under LSA 1x while lowest SOC stocks was NSA 0x. The relative intensities of the C-H bonds were higher in LSA 1x and also, was more effective in increasing soil hydrophobicity. Straw addition to conservation fields has limit and lessons leant from this study can serve as guide to African countries in the quest to been climate smart in conservation tillage farming.

Keywords: Straw Additions, Conservation Tillage, Conventional Tillage, No-Tillage, Soil Organic Carbon

Introduction

The accumulation of organic carbon in soils under conservation system compared conventional system provides better soil quality, carbon sequestration and goes to maintain a productive and sustainable agriculture system [1]. As the change to straw returning and straw mulching adaptation improved as cross the world, this study was premised on the basis of a long-term conservation trial which started since 2001 to study the effect of conservation tillage (CT) its related components within the Loess plateau dry farmlands of China specifically within the Gansu Province. Undisrupted studies on that field since its establishment in 2001 have shown that for the traditional conservation tillage field with straw returns (2500 kg/ha) yearly application of straw returns have not significantly improved the SOC content and its related components. With the main aim of providing further understanding on the effects that additional straw returning could have on a conservation tillage field.

The implementation of a sustainable management system of some soil practices like non-tillage, straw returning to fields and crop rotation are potential source of increase in carbon content in agricultural cultivated soils [2]. The returning crop residue into the soil can significantly change the chemical composition and concentration of soil organic matter (SOM) content [3]. Under conservation system, soils remain undisturbed as crop residues in the form of straw from previous cropping season are added to protect the soil; from exposure to environmental hazards and degradation [4,5].

Among the many essential elements needed to managed soils properly, tillage type, maintenance of soil organic matter content and the proper supply of soil nutrients are key. In order to be considered practicing conservation system, The Food and Agricultural Organization [6] gives the following guidelines which makes it is important that the system requires conditions, which resist environmental pollution and soil erosion. Such opposition is better appropriately attained either by protecting the soil surface with crop cover residues or by use of cover crops. FAO [7] has reported that the adaptation of conservation agriculture practices has been successfully in attaining higher crop productivity in a sustainable manner.

Conservation Tillage (CT) has different meanings in different countries and therefore the term is mostly adapted to suit the specific purposes of the area of practice in question [8]. The fundamental operating principle underlining the practice of CT is minimum soil disturbance. The practice and use of conservation tillage measures is continuously increasing worldwide according a World Bank report [9]. There is an increase in awareness by farmers worldwide of the negative effect of the traditional or conventional system of soil management.

Traditional Tillage (TT) or conventional tillage is a common practice of tilling the land using operations or techniques that are most commonly applied within a given location and have been used from generation to generation. This practice varies considerably and depends on the location and type of crop being grown. According to the CTIC, [10] TT involves incorporating residue but leaving less than 30% of the surface covered with residue after planting. ASAE, [11] defines TT as a sequence of operations, which is commonly or historically used in a given field to prepare seedbeds and produce crops. In China, conventional tillage mostly involves the use of moldboard mechanized ploughing to a depth of about 20 cm followed by harrowing, hoeing, rolling, and finally leveling the soil. Residues in the field removed are and mainly used as animal feed or fuel before the ploughing starts [12].

No tillage (no-till) system is the most common form of conservation tillage and as the name implies, it does not use tillage for the establishment of its seedbed. The soil is left undisturbed and the seeds are simply planted into previous year's crop residue. Minimal soil disturbance only occurs when applying fertilizers, use of seed disk openers or drills, row cleaners or seed furrow openers. No-till in principal should leave more (70%) of the surface cover with crop residue to be considered as a no tillage system. According to He et al. [13], no till makes about 50% of CT system in China and this corresponds to 1.33 Mha of farmland under this practice. Among the many tillage types practiced in most parts of the world, the common ones still extensively being practiced especially in northern China include mulch tillage, reduced tillage/minimum tillage, controlled traffic tillage, and permanent raised bed tillage. In no-tillage systems there is an improvement in the accumulation of (SOC), thereby supporting the efforts in climate change mitigation and also improving soil fertility Qi et al. [14].

According to Lal [15] SOC comprises of over 60% of total soil carbon and it thus greatly affects plant growth, soil physical and chemical properties, and environmental quality [16]. The decreasing rate of SOC contents in most agro-ecosystems are essential in the global C budget. The quantity of carbon retained in the soil are determined by several agronomic factors including crop residue management, tillage and crop rotation [17]. Some studies have reported that soils with minimal or no tillage had a greater SOC stocks than soils from conventional tillage systems [18, 19], while on the other hand, other studies reported the opposite [20] with others finding no significant differences among the major farming types [21]. Various studies have shown that organic residues such as crop residue returns when added to temperate soils decompose fast, with nearly one third of the original C content staying as soil organic matter (SOM) even after 1 year. It is known that crop residues such as straw returns are pre-cursors of the SOM stock, therefore, returning more crop residues to the soil is related with an increase in SOC concentration [22] but as to what extend and level of additional is acceptable remains unknown.

The practice of conservation tillage as reported by Zhu et al. [23] has an overwhelming impact on soil organic carbon (SOC), However, there is still a lack of ample understanding regarding the main factors that influence changes in SOC Also, Juhos et al. [24] reports that in conservation tillage which is a ploughless tillage and with a reduced number of tillage operations, it is clear on the role this tillage plays on soil functions and health. However, little is known on the comprehensive effects these fields have on the soil physical, chemical and biological properties. Furthermore, Li et al., [25], concludes that, the effect of long-term straw returning practices on SOC and its associated fractions is not properly understood and little attentiveness has been paid to it. Chemical composition of SOC will also affect the labile organic C fraction [26, 27]. However, some studies suggest that the use of straw residues with other forms of residual practices can alter the chemical composition of SOC [28]. Hence, understanding of the quantitative and qualitative characteristic of SOC sequestered in an agroecosystem is vital for exploring the possible processes, strategizes and mechanisms to increase in soil organic stocks [29].

This study monitored and evaluated the components of soil organic carbon content under the influence of different levels of additional exogenous organic inputs (straw) in order to master and understand the characteristics and relationship between this straw returning levels and their influencing factors. It has also been pointed out that for soils with high SOC content, the SOC does not increase without limit, but there is a limit value, that is, carbon saturation. [30, 31]. The results of some studies by Six et al. [32] and West et al. [33] show that in a relatively stable ecosystem, soil organic carbon is maintained in a more stable level, that is, the carbon input is equal to the carbon output, and when a factor changes in the system, causing the carbon input to be higher or lower than the carbon output, the soil organic carbon content will increase or decrease correspondingly, until a new stable level is reached. The carbon sequestration effect of different tillage system and straw returning to field has certain influence on soil organic carbon [34] and [35]. It has been found that different field treatment can reduce the loss of soil organic carbon by affecting soil organic carbon content, changing the components and proportions of organic carbon, improving soil nutrient environment, ensuring soil traits and increasing soil retention capacity [36].

In order to sustain the fertility of cultivated soils, there is need for an understanding of the characteristics and mechanisms leading to a maintainable sequestration of organic matter OM. It has been reported for several soil types under different climatic areas that tillage systems minimal soil disturbance (Eg. conservation tillage, reduced tillage, minimum tillage, or no tillage) usually increase the storage content of soil OM compared to traditional conventionally tillage system [37]. However, the processes and input levels underlying this increased OM sequestration are not completely understood.

Based on the results of previous studies on the estimation of soil carbon sequestration potential by soil management measures, the SOC content has a positive proportional linear relationship with exogenous organic carbon input levels, whether using the field test result extrapolation method or model simulation method [38]. However, studies by some researchers, point out that in some soils, although carbon inputs are been applied year after year, there has been no significant change in SOC content Song et al. [39]; and Basche et al. [40]. Improving soil carbon sequestration is of great significance for mitigating climate change and ensuring food security and can lead to better understanding of farmland management [41].

Following this, this study as guided with the broad objective of finding out the effects of tillage with additional straw returning on soil physiochemical properties and its influences on soil organic carbon stocks and its associated carbon components. It also, aims at drawing insight lessons and how it could be practicalized within the African context to benefit already existing local interventions on conservation tillage farming.

Materials and Methods

The study was conducted within the Loess Plateau of China, the area has a total land size of about 62.4×10^4 km^2. The area is subjected to human population, natural resource and environmental pressures. Relying on a long term-term conservation tillage field experimental trial which commenced since 2001 in Li Jiabu town (35°28′N, 104°44′E 1971 m.a.s.l) near Dingxi city of the Gansu Province of China. Just as in many African regions, the study site is a typically rain-fed area but has experienced a rather long and continuous history of cropping using conventional tillage system.

The study was conducted mainly on two existing tillage system treatment plots. A conservation field of no tillage with straw returns (NTS) and a conventional tillage field with straw returns (TS). Spring wheat (cv. Dingxi No.35) was planted on each experimental plot and arranged in a complete randomized block design. Four (4) different additional wheat straw return levels were applied to each treatment unit and replicated three times (n = 3), with treatment sizes measuring 4 m wide × 6 m long. All crop residues from the previous season were returned to the original plots after threshing and spread evenly on the soil surface while additional straw was crashed and or milled, weigh and added to individual treatment plots. Data was collected during the 2022 and 2023 cropping seasons.

Table.1: Straw returning volume levels

Treatment code	Levels of straw returning additions	Volume of straw (kg/ha)
NSA 0x	No Straw Addition	0
LSA 1x	Low Straw Addition	3500
MSA 2x	Medium Straw Addition	7000
HSA 3x	High Straw Addition	10500

Determination of initial soil properties, SOC and liable C fractions

Soil samples were air dried after animal, plant, stones and unwanted residues were removed, and then sieved (2 mm) for soil properties analysis except in the case for bulk density (BD). Soil texture determination was done by the pipette method while the soil pH was measured on the base of a soil to water extract ratio (i.e. 1:2.5). The measurement of most soil physico-chemical properties followed the methods as described by Zheng [42] while BD was measured through oven-drying method.

The SOC content which is the amount of carbon in a soil sample relative to the total mineral content of the sample. It is usually expressed as a (mass) percentage. SOC content was measured by the potassium dichromate ($K_2Cr_2O_7$) rapid oxidation method as described in Nelson and Sommers [43].

Microbial biomass carbon (MBC) was determined by the chloroform fumigation and extraction (FE) method as explained by Ladd and Amato [44]. Every replicate was divided into two equal parts, with the first part fumigated with ethanol-free chloroform for 24 hours, and the other part was non-fumigated or control. Both samples of fumigated and non-fumigated soils were placed on a shaker for 30 minutes with 0.5 M K_2SO_4 (1:5 soil: extraction ratio), centrifuged and filtered. The soil MBC was calculated by dividing the difference in the extractable carbon between the fumigated and non-fumigated soils, with a conversion factor 0.45.

Particulate organic carbon (POC) was determined using the method as described by Li et al. [27]. In this, 20g soil sample was the air-dried and mixed with sodium hexametaphosphate (5 g L^{-1}) solution then shaking at 90 r min^{-1} for 18 hours. The scattered soil solution was then wet sieved through 0.053 mm sieve using a continuous flowing distilled water. All the retained soil samples on the sieve was washed and the oven dried at 60 ^{0}C for 48 hours and ground to measure POC content [45]. Dissolved organic carbon (DOC) was also determined and calculated using appropriate equations as recommended by Vuong et al. [46] and Yang et al. [47].

Determination of SOC Stocks, Management Index and Grain Yield

Soil organic carbon stocks are generally expressed in tones or mg per hectare for a chosen depth and commonly restricted to the fraction < 2mm in size. To determine SOC stocks, this study quantified within the 0-30 cm soil sampling depth. Also, the following was considered; (i) SOC content of the fine earth mass (< 2 mm size), (ii) the coarse mineral fraction content (> 2 mm size) and, (iii) the determined soil bulk density.

To be able to quantify soil organic carbon stocks (mg C ha^{-1}), different soil mass equations and indices was used as described by Ellert and Bettany, [48]; Xu et al. [49]. The soil organic carbon stocks are grounded on an equivalent soil mass equation (mg C ha^{-1}) from which calculation is made as SOC stocks within the top soil layers (0-5 cm). This is due to the already established fact of a significant change in within those soil depths. An aluminum tin soil cores that contained the sampled soil were oven dried at 105^{0}C for 48 hours.

Furthermore, grain yield was determined based on dry weight. This was achieved by employing oven-drying at 105°C for 45 minutes and then drying to a constant weight at 85°C. Net primary productivity (NPP) was also assessed using the method as described by Bolinder et al. [50]. The calculation of soil carbon management index (SCMI), Carbon pool index (CPI) and lability index (LI) and grain yields were done using appropriate formulae.-

The effect of additional straw returning to tillage treatments on soil properties, SOC content and its associated components were analyzed statistically using the procedure for analysis of variance (ANOVA) of the SPSS package version 24 (IBM Company, New York, USA) with significance set at 5%. One-way analysis of variance (ANOVA) was conducted to determine treatment effects on straw returning levels.

Results and Discussion

Effects of Additional Straw Returning on Soil Properties, Characteristics and Crop Yield

Baseline data (table 2) taken on all potential soil parameters that may have an influence on some of the main study indices. This was taken at the start of the experiment before the application of study treatment to both NTS and TS fields. Results from the physical properties of the study site show that proportions of sand and silt were significant ($P \leq 0.05$) at both fields. Soils at both fields were low clay showing no significant difference. All soil in both fields had high calcium carbonate

($CaCO_3$) concentration, while pH and EC values were not significant. Also, bulk density in both fields were not significant. The study area was clay loam textured with a significant percentage of porosity between tillage fields. Furthermore, a comparison of the two fields showed that, apart from soil porosity, field capacity and soil moisture were not significant.

For the chemical properties, this study shows that soil organic carbon (SOC), soil organic matter (SOM) and total available nitrogen (N) was significantly ($P \leq 0.01$) higher in NTS fields than in TS fields. C/N ratios in both fields was 8.48 and 8.28 in NTS and TS fields respectively and showing no significant difference. The differences in the computed SOC and total N stocks between NTS and TS fields were similar to those in SOC and total N concentrations because no significant change in bulk density was observed even with the use of tillage practice in TS fields. The mean SOC and N stocks were 13.37 mg C $ha^{-1}$and 1.50 mg N $ha^{-1}$for in both fields. NTS showed a much higher content of SOC and total N stock over TS. Available P and K taken from both study fields were not significant although their content was high in NTS.

Table 2: Selected soil properties at the start of the experiment at both tillage fields

Soil Properties	NTS	TS	t	p
Physical Properties				
Sand (1 – 0.05 mm) (%)	59.80 ± 3.82	63.10 ± 4.39	-3.172	0.017**
Silt (0.05 – 0.002 mm) (%)	28.61 ± 2.20	26.31 ± 2.12	2.863	0.014**
Clay (< 0.002 mm) (%)	10.90 ± 1.91	10.61 ± 1.30	0.846	0.411
Texture	Clay loam	Clay loam	--	--
Bulk density (g cm^{-3})	1.36 ± 0.09	1.38 ± 0.09	-1.778	0.114
Porosity (%)	56.90 ± 3.10	62.40 ± 4.55	-2.578	<0.001*
Field Capacity (%)	31.45 ± 2.30	32.35 ± 3.85	1.78	0.794
Soil Moisture (%)	13.35 ± 1.36	13.46 ± 1.22	0.725	0.541
Chemical Properties				
SOC (g kg^{-1})	8.73 ± 1.25	7.57 ± 1.34	6.725	<0.001*
SOM (%)	3.65 ± 0.36	1.95 ± 0.46	2.650	<0.001*
Total N (g kg^{-1})	0.81 ± 0.07	0.68 ± 0.06	4.773	<0.001*
C/N	8.49 ± 1.36	8.29 ± 1.12	0.722	0.478
Available P (mg kg^{-1})	24.71 ± 1.46	21.72 ± 2.65	0.845	0.345
Available K (mg kg^{-1})	132.50 ± 10.70	130.50 ± 11.34	4.563	0.876
$CaCO_3$(g kg^{-1})	103.2 ± 8.30	102.3 ± 8.01	0.261	0.794
pH (H_2O)	9.11 ± 0.19	9.09 ± 0.14	1.135	0.894
EC (Is cm^{-1})	126.5 ± 10.80	116.1 ± 9.21	0.978	0.348
SOC storage (mg ha^{-1})	14.51 ± 2.90	12.25 ± 2.05	6.191	<0.001*
Total N storage (mg ha^{-1})	1.65 ± 0.21	1.37 ± 0.14	4.813	<0.001*
Data are Mean ± SD				
**** Significantly different at 0.01 confidence level (t-test, p ≤ 0.01)***				
***** Significantly different at 0.05 confidence level (t-test, p ≤ 0.05***				

In a similar study by Farahani et al. [51], they found that the effects of tillage systems on soil physical properties are strongly dependent on SOC. Fan et al. [52] after two years of experiment reported that returning crop straws effectively improved the soil physiochemical properties at varying levels of soil depths. It is also reported that tillage practices which directly affects the soil, has a direct influence on the plant's general growth and yield [53] Other factors to consider in order to increase crop yields and to meet demand is to improve the utilization of agricultural lands [54]. And as recommended by Mueller et al., [55] straw returns on the soil can influence the biological and physiochemical attributes of a soil. The high percentage (about 60%) of total soil carbon available in the soil as SOC has a great influence on plant growth, soil physical and chemical properties, and environmental quality [16].

SOC, plays a vital role in crop yields, a study by Blanco-Canqui et al. [56] found that a 0.1% increase in SOC concentration increased sorghum yield by 0.36 mg ha^{-1}(5.7 bu ac^{-1}) and wheat yield by 0.04 mg ha^{-1}(0.67 bu ac^{-1}) at 0 kg N ha^{-1}. Organic residue amendments are usually added to crop fields into order to increase crop yield or quality [57]

Bulk density at both TS and NTS were not significant. Climatic variations and extreme climatic events can result in changes in soil moisture contents and consequently lead to availability of carbon and other soil nutrients [58] and the mineralization of SOC [59, 60]. Furthermore, Intensive farming practices and the consistent removal of crop residues [14] in the Loess plateau has negative effects on soil fertility [61].

Table 3: Effects of straw addition treatment with tillage types and their interaction on grain yield and harvest index for spring wheat field

Source of variation	**Grain yield**	**Harvest index**
Straw Addition Treatments (SAT)	***	NS
Tillage Types (TT)	***	**
ST × TT	NS	NS
, **, *** indicate significant difference at P < 0.05, P < 0.01, P < 0.001 respectively		

NS indicate no significance difference at P < 0.05

Table 4: Effects of straw addition treatment with tillage types and their interaction on grain yield and harvest index for spring field Pea

Source of variation	**Grain yield**	**Harvest index**
Straw Addition Treatments (SAT)	**	NS
Tillage Types (TT)	*	**
ST × TT	NS	NS
, **, *** indicate significant difference at P < 0.05, P < 0.01, P < 0.001 respectively		

NS indicate no significance difference at P < 0.05

A general analysis of variance was carried out to describe the interaction between main treatments on the yield and harvest output. It is clearly indicated (Table 3) that straw addition treatment and the tillage field types were significant in grain yield during the spring wheat cropping season. However, their interaction was not significant for both grain yield and harvest index. A similar trend was observed for the field pea cropping season (Table 4) where no significant difference was observed in the treatment interactions.

At the end of each cropping season and in order to determine the effects straw additions on crop harvest, grain yield and the net primary productivity (NPP) were analyzed and calculated for. The application of straw additions to tillage fields significantly affected grain yields especially in spring wheat fields. NTS fields had higher grain yields compared to TS fields. Treatment fields with no and low straw additions (NSA 0x and LSA 1x) recording higher yields in wheat fields whiles for pea fields, low straw additions and medium straw additions (LSA 1x and MSA 2x) had higher and significant yields. Studies on the long term effects of tillage on soil physical properties and crop yield is very important as this can contribute to the growing body of information on sustainable agriculture Steponaviˇcien˙ e et al. [62].

The net primary productivity analysis results show significantly higher productivity values in NTS than in TS. With treatments of no, low and medium straw additions (NSA 0x, LSA 1x, and MSA 2x) obtaining higher values.

This study's findings on yield indices is consistent with that from Yeboah et al. [63] who reported higher net primary productivity levels in NTS fields compared to TS fields. Furthermore, Huang et al. [64] within the same study area reported that improved SOC under NTS fields serves as nutrient source which could support higher crop productivity. The study of net primary productivity is an essential aspect that contributes to the calculation of carbon inputs in soil and can be utilized to improve soil carbon dynamics prediction and management.

Effects of Additional Straw Returning on SOC

This study showed that compared to the no straw addition (NSA 0x), the continues and increasing application of straw on NTS fields had higher soil organic carbon content at the top soil layers during the first season of wheat cropping. The average trend of SOC content ranged from 5.56 – 20.77 g kg^{-1} within the wheat field. Also, the upper soil layers, low straw addition (LSA 1x) to treatments recorded significantly higher contents of SOC over the other three straw returning treatments in both harvesting seasons of wheat and pea fields. LSA 1x straw returning treatment significantly increased the total SOC content of the TS fields by 16.0% – 25.0% in the first cropping season and by 22% - 27% in the second cropping season under wheat and pea cropping rotation. The general straw addition treatment effect on SOC content trend across tillage types with straw returning was; LSA 1x > NSA 0x > MSA 2x > HSA 3x.

Soil organic carbon stocks was determined to understand its effect on treatments. Averagely, soil organic carbon stocks ranged from 31.5 to 37.4 mg ha^{-1} in the first season and 32.4 to 49.3 mg ha^{-1} in the second cropping season. Highest accumulated SOC stocks was observed under medium straw addition treatment (LSA 1x) in both cropping seasons. Lowest SOC stocks was recorded at the no straw addition treatment (NSA 0x). Comparing between TS and NTS additional straw treatment did not record significant effect across the two cropping seasons for both wheat and pea.

According to several research findings by Six et al. [65], tillage type influence on SOC can be linked to regional characteristics such as soil type, residue management, crop rotation, region, and land management strategies. A study by Singh et al. [66] found that crop planting practices and residue management raised SOC considerably after 5 years at depths of 0-15 and 15-30 cm. Higher SOC concentration in the surface layer of straw returning NTS and TS treatment plots may be linked to greater inputs of straw residue, resulting in high SOC retention in surface soil [67]

SOC contributes about 60% of total soil carbon and this significant proportion affects the properties of the soil. [15]. Different filed treatment including residue returns and tillage types can lower the loss of SOC by affecting soil organic carbon content, changing the components and proportions of organic carbon, improving soil nutrient environment, ensuring soil traits and increasing soil retention capacity [36].

Table 5: Effects of soil organic carbon content (g kg^{-1}) on additional straw returning treatments and tillage types

Depth (cm)	Treatment	Wheat 2022				Pea 2023			
		NTS	±	TS	±	NTS	±	TS	±
0-5	NSA 0x	17.1	0.09d	15.11	0.05c	19.86	0.31c	18.17	0.12c
	LSA 1x	20.77	0.01a	19.08	0.09a	25.45	0.09a	21.18	0.04a
	MSA 2x	18.05	0.06c	16.36	0.11bc	20.17	0.05b	18.86	0.03b
	HSA 3x	19.34	0.11b	17.97	0.06b	21.06	0.01b	21.00	0.09a
5-10	NSA 0x	14.91	0.09c	10.21	0.06d	16.27	0.02d	16.91	0.09c
	LSA 1x	20.43	0.04a	16.75	0.09a	22.74	0.02a	19.45	0.09a
	MSA 2x	16.34	0.04b	15.06	0.06b	18.92	0.08b	18.72	0.11b
	HSA 3x	15.19	0.05c	10.91	0.05c	17.36	0.07c	18.24	0.02b
10-30	NSA 0x	6.56	0.21b	7.63	0.11a	9.36	0.08a	9.06	0.18b
	LSA 1x	7.26	0.06a	6.85	0.17b	8.86	0.06b	10.45	0.41a
	MSA 2x	5.90	0.09bc	6.88	0.09b	7.08	0.21c	7.05	0.02c
	HSA 3x	5.65	0.11c	6.92	0.05b	8.88	0.11b	9.78	0.21b
Mean ± SD followed by the same letter in a column are not significantly different (P = 0.05)									

Effects of Additional Straw Returning on Other Associated Carbon Components

Diverse content of MBC was observed among treatments at the different depths in the two cropping seasons of wheat and pea systems. The no additional straw (NSA 0x) and low levels of straw additions (LSA 1x) resulted in some significantly higher levels soil MBC compared to medium and high levels of straw returns. (table 6). Depending on tillage type, soil MBC content was wide, ranging from 220. 46 to 325.12 mg kg^{-1}, 210.24 to 314.48 mg kg^{-1} and 215.10 to 290.65 mg kg^{-1}. Intensifying soil organic carbon is normally accompanied by an equal increase in MBC, as the SOM offers the microorganisms primary substrates and sources [27]. MBC content was connected to SOC content not just near the surface, but also at lower depths. Studies by Naresh et al. [68], found that tillage techniques could change the dynamics of microbial biomass in soils and organic soil carbon by varying the aggregate and distribution of carbon therein.

The content of dissolve organic carbon (DOC) concentrations were higher under NSA 0x and LSA 1x straw addition treatments. MSA 2x treatment increased the DOC concentration by 11% in relation to NSA 0x treatment, whiles LSA 1x increased the DOC concentration by 14% compared to HSA 3x. However, at the lower soil layers, NSA 0x treatment increased DOC concentration by 11% in comparison with MSA 2x.

Among the other associated carbon components, particulate organic carbon (POC) fraction of the upper soil layers saw NTS been highly significant (table 8). The mean POC contents under low straw addition treatment (LSA 1x) varied from 0.92 to 1.04 g kg^{-1}. The LSA 1x treatment had a significant buildup of POC in comparison to high levels of straw additions (HSA 3x) which had 0.46 to 0.59 g kg^{-1} and that of no straw addition treatment (NSA 1x) which had 0.31 g kg^{-1} to 0.48 g kg^{-1} respectively in both fields.

The easily oxidizable carbon (EOC) content (table 9) was significantly higher under low straw addition treatment (LSA 1x) (4.82 g kg^{-1}) and under medium straw addition (MSA 2x) (4.46 g kg^{-1}) compared to the no straw addition (NSA 0x) and high straw additions (HSA 3x). Additional straw return treatment increased the EOC content by 10% - 30% compared the high straw additions levels (HSA

3x). The medium straw addition treatment (MSA 2x) also significantly increased the EOC content by 17% comparing to HSA 3x treatment at the upper soil layer, and was 6% higher under at the lower soil layers.

Under straw returning treatments, the higher the EOC, the better and fresher the organic matter inputs to the soil in the 20-40 cm layer [69]. There was a higher amount of EOC in straw returning treatments at both soil levels in this study, indicating a faster rate of SOM decomposition and nutrient cycling, which will speed up through mineralization the modification of its nutrient [70]. There was a higher amount of EOC in straw returning treatments at both soil levels in this study, this therefore implies that there is a quicker rate of SOM decomposition and cycling of nutrients.

Table 6: Effects of microbial organic carbon (mg kg^{-1}) on additional straw returning treatments and tillage types

Depth (cm)	Treatment	Wheat 2022				Pea 2023			
		NTS	±	TS	±	NTS	±	TS	±
0-5	NSA 0x	249.44	2.31c	220.44	2.00d	260.09	1.30c	225.81	0.90c
	LSA 1x	322.77	1.58a	270.38	0.98a	325.11	0.66a	319.22	1.00a
	MSA 2x	315.68	1.21ab	251.47	1.01b	326.29	1.00a	312.11	2.00ab
	HSA 3x	280.17	0.55b	232.76	0.10c	296.74	0.34b	262.44	1.90b
5-10	NSA 0x	251.84	2.10c	210.29	1.00d	255.36	1.10d	238.82	1.35c
	LSA 1x	264.83	1.15b	234.47	2.35c	268.36	1.20c	250.05	1.00b
	MSA 2x	290.32	1.01a	265.22	1.00b	314.47	1.35a	291.29	1.20a
	HSA 3x	288.21	1.21a	276.21	2.00a	294.37	1.00b	297.15	1.90a
10-30	NSA 0x	200.74	1.59b	195.05	1.00c	225.8	0.34c	212.81	1.45c
	LSA 1x	269.53	1.06a	245.33	2.01a	276.64	0.90a	250.64	2.31c
	MSA 2x	263.65	2.91a	219.44	0.87b	270.73	1.45ab	236.45	1.21c
	HSA 3x	202.17	1.05b	200.18	0.88c	247.08	1.34b	203.35	0.60c
Mean ± SD followed by the same letter in a column are not significantly different (P= 0.05)									

Table 7: Effects of dissolved organic carbon (mg kg^{-1}) on additional straw returning treatments and tillage types

Depth (cm)	Treatment	Wheat 2022				Pea 2023			
		NTS	±	TS	±	NTS	±	TS	±
0-5	NSA 0x	243.38	1.01c	192.45	0.89b	251.37	1.30d	231.43	0.89c
	LSA 1x	309.35	1.30a	204.02	1.20a	317.34	0.77a	268.15	1.25a
	MSA 2x	285.42	1.45ab	199.84	1.00a	298.19	0.90b	250.88	1.91b
	HSA 3x	259.35	1.31b	195.34	1.35ab	267.33	1.30c	245.26	1.24bc
5-10	NSA 0x	215.5	1.44c	218.13	1.01c	229.4	1.95d	225.38	1.45c
	LSA 1x	258.86	0.71a	231.46	1.33a	262.35	1.20a	241.86	1.70a
	MSA 2x	248.76	1.90ab	228.84	0.89a	250.24	1.50b	233.63	1.42b
	HSA 3x	238.66	1.00b	224.12	1.34b	235.32	1.30c	231.29	1.51b

10-30	NSA 0x	252.43	1.31a	190.06	1.22a	256.42	1.70a	241.22	1.71a
	LSA 1x	232.76	1.59ab	186.34	0.88a	246.05	1.56a	229.82	1.20b
	MSA 2x	215.99	1.45b	183.28	1.14a	236.74	1.11ab	204.55	0.94c
	HSA 3x	222.32	0.91b	180.44	0.90a	230.12	1.00b	202.44	0.67c
Mean ± SD followed by the same letter in a column are not significantly different (P = 0.05)									

Table 8: Effects particulate organic carbon (g kg^{-1}) on additional straw returning treatments and tillage types

Depth (cm)	Treatment	Wheat 2022				Pea 2023			
		NTS	±	TS	±	NTS	±	TS	±
0-5	NSA 0x	0.31	0.05d	0.34	0.02d	0.41	0.04d	0.33	0.03d
	LSA 1x	1.04	0.02a	0.92	0.05a	0.95	0.01a	0.92	0.05a
	MSA 2x	0.78	0.01b	0.71	0.07b	0.82	0.04b	0.84	0.05b
	HSA 3x	0.46	0.03c	0.46	0.04c	0.59	0.04c	0.55	0.07c
5-10	NSA 0x	0.29	0.01c	0.24	0.02d	0.48	0.04c	0.38	0.09d
	LSA 1x	0.84	0.08a	0.82	0.08a	0.85	0.01a	0.89	0.01a
	MSA 2x	0.62	0.06b	0.53	0.06b	0.81	0.05ab	0.67	0.03b
	HSA 3x	0.65	0.05ab	0.47	0.02c	0.58	0.02b	0.56	0.07c
10-30	NSA 0x	0.25	0.04d	0.26	0.03c	0.35	0.05d	0.28	0.03c
	LSA 1x	0.63	0.06a	0.46	0.06a	0.65	0.02a	0.48	0.02a
	MSA 2x	0.58	0.05b	0.42	0.04ab	0.59	0.01b	0.43	0.02b
	HSA 3x	0.27	0.02c	0.37	0.07b	0.43	0.03c	0.44	0.06b
Mean ± SD followed by the same letter in a column are not significantly different (P= 0.05)									

Table 9: Effects of easily oxidizable carbon (g kg^{-1}) on additional straw returning treatments and tillage types

Depth (cm)	Treatment	Wheat 2022				Pea 2023			
		NTS	±	TS	±	NTS	±	TS	±
0-5	NSA 0x	3.75	0.04d	3.57	0.02c	3.76	0.03d	3.65	0.05d
	LSA 1x	4.75	0.02a	4.55	0.07a	4.81	0.06a	4.92	0.09a
	MSA 2x	4.34	0.03c	4.25	0.01b	4.39	0.05c	4.33	0.07c
	HSA 3x	4.55	0.07b	4.41	0.03ab	4.62	0.08b	4.66	0.03b
5-10	NSA 0x	3.53	0.05d	3.24	0.05d	3.84	0.01d	3.44	0.04d
	LSA 1x	4.64	0.09a	4.33	0.05a	4.82	0.04a	4.45	0.07a
	MSA 2x	4.36	0.05c	4.10	0.08b	4.46	0.02c	4.25	0.01b
	HSA 3x	3.75	0.03b	3.56	0.03c	4.67	0.06b	3.67	0.02c

10-30	NSA 0x	2.81	0.11d	2.84	0.09c	2.79	0.07d	2.9	0.10c
	LSA 1x	3.32	0.09a	2.99	0.05a	3.37	0.11a	3.32	
	MSA 2x	3.03	0.09c	2.91	0.05b	3.18	0.08c	3	0.09b
	HSA 3x	3.12	0.04b	2.96	0.11ab	3.22	0.05b	3.31	0.21a
Mean ± SD followed by the same letter in a column are not significantly different (P= 0.05)									

Effects of Additional Straw Returning on Carbon Indices

Three indices namely, soil carbon management index (SCMI), liability index (LI) and carbon pool index (CPI) were computed for. These indices were computed based on a general bulk soil basis. The additional straw returns and tillage types had significant effect on CPI, LI and SCMI (table 10). Highest SCMI (149) were observed during the second cropping season. In both tillage fields, the following SCMI order was observed LSA 1x >MSA 2x >HSA 3x >NSA 0x. Comparing with NSA 0x, LI and CPI increased under high straw additions (HSA 3x). LI was highest under TS field in the second cropping season and CPI was highest under NTS also in the second cropping season.

SCMI is derived on the basis of changes in the calculation of EOC and total SOC stemming from different soil management practices [71]. Soil carbon management index (SCMI) is a soil index that can be used to evaluate agricultural management strategies [71]. Similarly, Moharana et al., [72] found that if the SCMI value is greater than 100, an agricultural management system can be called sustainable. Vieira et al [71] revealed that lability of C and SCMI showed a relationship that is close with the annual cycle of pea and wheat straw returns in the soil coupled with less disturbance under NTS. The findings of this study which show and increase in the liability index (LI) and carbon pool index (CPI) in low straw addition treatments as compared to no straw addition treatment is similar to the findings of Li et al. [25].

Table 10: Effects of soil carbon management indices on additional straw returning treatments and tillage types

Treatment	Wheat 2022				Pea 2023			
	NTS	**±**	**TS**	**±**	**NTS**	**±**	**TS**	**±**
CPI								
NSA 0x	1.02	0.02b	1.01	0.05b	1.01	0.03b	1.00	0.12c
LSA 1x	1.07	0.01a	1.26	0.00a	1.28	0.07a	1.09	0.01a
MSA 2x	0.98	0.01b	1.19	0.00a	1.06	0.05b	1.04	0.14a
HSA 3x	0.92	0.03b	1.08	0.07b	1.02	0.06b	0.92	0.20b
LI								
NSA 0x	0.98	0.11b	0.99	0.08b	1.01	0.20b	0.98	0.02b
LSA 1x	1.28	0.08a	0.98	0.01b	1.22	0.15a	1.26	0.01a
MSA 2x	1.24	0.05a	0.95	0.02b	1.16	0.07a	1.27	0.05a
HSA 3x	1.32	0.09a	1.06	0.09a	1.31	0.05a	1.36	0.04a
SCMI								
NSA 0x	98	0.40c	99	0.30c	102	0.20c	98	0.20c
LSA 1x	131	3.45a	120	0.09a	149	0.24a	139	2.45a
MSA 2x	126	3.40b	117	0.20a	130	0.34b	131	0.30a
HSA 3x	121	3.25b	115	0.10b	132	0.32b	124	1.45b

Mean ± SD followed by the same letter in a column are not significantly different (P = 0.05)

FTIR spectra analysis of SOC structural characteristics of straw addition treatments

The four different straw addition treatment levels were analyzed using the Fourier-transform infrared (FTIR) spectroscopy and to establish the intensity of the functional groups of C and H bonds within those levels of straw treatments. Bulk soil samples across study treatments sampled and the results show that, compared to the NSA 0x, the relative intensities of the C-H bonds were higher at LSA 1x, while the changes in vibration of the C = O bonds is shown in table 11. According to the corresponding absorption peaks, LSA 1x had higher relative intensity of C-H bands than the other straw addition treatments. LSA 1x on the same hand, had lower relative intensities of C = O bonds. Meanwhile, compared with NSA 0x, HSA 3x had no change of relative intensities of C = O bonds. The ratio of the relative intensities of C-H and C = O was used to calculate the hydrophobicity index (HB). The results of this study show that the HB value was higher under less straw addition treatments especially in the case of LSA 1x.

FTIR spectroscopy has shown that the hydrophilic functional group of the C = O bonds determines the adsorption performance of the organic matter, and the hydrophobic functional group of the C-H bonds determines the wettability of the organic matter. The relative content of these functional groups is related to SOC content. This study shows that, the relative intensities of the C-H bonds and hydrophobicity (HB) values were higher under LSA 1x, but had lower relative intensities of C = O bonds. This result illustrates that a lower level of straw addition was more effective in increasing soil HB and improved the activation of soil organic matter. A similar and significant contribution to SOC is also reported by Leifeld et al. [73]. The low addition of straw treatments did not only increase SOC contents, but also the compounds of aliphatic, aromatic and carbohydrate SOM and this increase could enhance the chemical recalcitrance of SOM and prevent microbial decomposition. Zhou et al. [74] reported similar stability mechanisms by molecular recalcitrance contributed to the accumulation of SOC in some paddy soils under long term management. Since straw additions is a complex organic amendment process, it is affected by the structural characteristics of soil organic carbon.

Table 11: Relative intensity of the main functional groups in FTIR spectra of SOC relative to the different straw addition treatments

Straw Addition Treatment	Relative Intensity (%)		Hydrophobicity Index (HB)
	C-H	C = H	C-H / C = H
NSA 0x	0.828	7.294	0.114
LSA 1x	2.106	4.326	0.487
MSA 2x	1.569	5.520	0.281
HSA 3x	1.283	7.299	0.176

Conclusion and Recommendation

Both tillage with straw returns (TS) and no tillage with straw returns (NTS) showed some varied proportions of physical and chemical soil properties. Study fields were significant in their proportions of sand and silt. All soil in both fields had high calcium carbonate ($CaCO_3$) concentration, pH and EC values. SOC, SOM and total available N was significantly ($P \leq 0.01$) higher in NTS fields than in TS fields. Among the most significant effect of straw addition treatment noticed was a decrease in soil bulk density.

Study showed that SOC content ranged from 5.56-20.77 g kg^{-1} and that on existing conservation fields with straw returns, SOC content was not immediately and significantly affected by higher levels of straw addition. NTS fields recorded significantly higher contents of SOC. The observed trend in terms of the effect of straw addition levels on SOC content was LSA 1x > NSA 0x > MSA 2x > HSA 3x.

This study revealed a significant increase in SOC content of most organic carbon components; including SOC, MBC, DOC, POC, EOC in NTS fields as compared to TS fields for both study crops. MBC content of the upper soil surface in LSA 1x treatment was significantly higher. POC fractions was most influenced by tillage type and straw additions and was highly significant at the upper soil layers on NTS fields. EOC was significantly higher under LSA 1x and MSA 2x straw addition treatment. Study results further revealed that straw addition treatments of LSA 1x, NSA 0x, MSA 2x, and HSA 3x showed relatively good improvement on all fractions of SOC. The additional straw returns and tillage types had significant effect on LI, CPI and SCMI. Highest accumulation of SOC stock was observed under medium straw addition treatment (MSA 2x) in both cropping seasons.

Analysis of the chemical composition of bulk soil samples for the various treatments showed that compared to the NSA 0x, the relative intensities of the C-H bonds were higher with LSA 1x Hydrophobicity index value was higher under lower straw addition treatments.

In the wake of rising awareness of the importance of conservation tillage system and farming It is concluded that this study findings would offer African scientist and agroecologist, an insight in better understanding the mechanisms and effects of additional straw returns on this very important component of soil organic carbon and its associated components especially when interested in the long-term farming system. This would support the efforts of mitigating declining crop production yields, improving soil health and increasing soil carbon content. There is need to further explore in future a continuation of this study with the use of newly developed methods and novel bio-marker (GC/MS) techniques to understand the chemical characteristics that these straw addition treatments may play on the chemical and biological process of the organic carbon contents. It is further recommended that similar long-term study sites should be set in most research station field in Africa for long-term study purposes, and already existing conservation fields could consider repeating this study to help validate the findings of this study within the African context.

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Improving Pearl Millet Production in Senegal's Semi-arid zone Through Participatory Research for Farm-level Intervention across rainfall gradients

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Abstract:

Assessing the suitability of crops in different agroclimatic zones is critical to reducing climate risk and mitigating the impacts of climate change on agricultural production. This study adopts a participatory extension approach (PREA) to accelerate adaptation measures to minimize climate risks on millet production. The study evaluates the performance of dual-purpose varieties (Thialack 2, SL 28, and SL 423) compared to farmers ' improved local variety (Souna-3) under integrated soil fertility management (ISFM) using a micro-dosing strategy. The impact of improved density, dual-purpose, and micro-dosing technology under high population on grain and stover yields during the growing seasons of 2022 and 2023 were accessed across three clusters in Senegal. Our results showed the performance of dual-purpose varieties, with notable in yield gain of 37% in Thiel, 15% in Meouane, and 8% in Daga Birame clusters compared to improved local. However, the results revealed no significant variety and fertilizer effects ($P>0.05$). Furthermore, improved density (25,000 hills ha^{-1}) exhibited a notable yield increase with a significant effect ($P<0.05$) of grain yield compared to farmers' practice, exhibited yield gain of 56% in Thiel, 51% in Meouane, and 53% in Daga Birame clusters respectively. Stover yield also respectively increase by 55%, 62%, and 64% across clusters. Considering the changing climatic conditions, adopting such practices at the field scale could further enhance grain yields and increase fodder availability for livestock.

Keywords: Pearl Millet, Micro-dosing, High density, climate variability and change, Dual-purpose, Improved local

Introduction

In Senegal, millet is a crucial crop to achieve food and nutrition security since it is one of the staple crops cultivated under a mono-crop farming system throughout the country (Diatta & Thomason, 2016; Faye *et al.*, 2023; Faye *et al.*, 2018). Millet withstands dry conditions of 300 mm annual rainfall and remains green at very low moisture levels (Vieira Junior *et al.*, 2023; Yadav *et al.*, 2017). Despite this position, the yield of millet is low at the farmer scale compared to the potential yield. This poor performance is mainly due to low productivity linked to the low level of fertilizer use (Adiku *et al.*, 2015), poor management, along with the poor performance of the livestock sector (Diouf *et al.*, 2019; Ouedraogo *et al.*, 2018) combine more and more to climate effects. Consequently, in Senegal, farmer millet yields rank between 500 to 900 kg ha^{-1} which remains far from the potential yield (Faye *et al.*, 2023). The micro-dosing strategy, which consists of applying small doses of fertilizer in the planting hills has proven to be a good opportunity to improve crop productivity and farmers' incomes(Akinseye, *et al.*, 2023; Tabo *et al.*, 2007). This strategy is an approach, that promises a more sustainable and resilient future for food systems by minimizing damage to natural resources, reducing the use of chemical inputs, and increasing yield and social inclusion (Tabo *et al.*,2007). Furthermore, the application of a micro-dosing fertilizer strategy enables farmers to overcome the risks associated with fertilizer use under conditions of low soil moisture (Vanlauwe *et al.*, 2023) since it improves nitrogen uptake and reduces fertilizer loss (Bationo & Waswa, 2011).

The combination of organic resources and mineral fertilizer as inputs formed the technical backbone of integrated soil fertility management (ISFM), especially when adopting micro-dose application strategies (Akinseye, *et al.*, 2023). Additionally, micro-dosing which has been demonstrated to be beneficial for smallholder farmers, Faye *et al.* (2023) and Pilloni *et al.* (2022) have demonstrated that increasing plant density up to 25,000 hill/ha enhances significantly grain and stover yields compared to farmers' plant population (12,500 hill/ha. Thus, technology adoption remains low due to limited access to inorganic fertilizers due to high market prices and inadequate use of manure amendments (Raes *et a*l., 2021; Waongo *et al.*, 2015). Thereby, given the considerable gap between farmer yields as mentioned above and cultivar's yield potential, this study aimed to evaluate the performance of newly released dual-purpose varieties coupled with high density and micro-dosing strategy at the farm scale compared to Souna 3, the common farmers' variety grown throughout the country. Hence, the interventions in this study follow the participatory research and extension approach (PREA) which is expected to accelerate the adoption of CSA packages dissemination toward climate risk management (Ajeigbe & Dashiell, 2010). It serves as a stepping stone for raising awareness of millet management and its suitability for cultivation under challenging and changing climatic conditions.

Materials and Method

Study area

The data were collected from on-farm participatory demonstration trials established across the three (Thiel, Meouane, and Daga Birame) selected clusters within the Senegal Sudano-Sahelian zone during the growing seasons of 2022 and 2023. Both Meouane and Daga Birame clusters are located within the peanut basin while Thiel is located in the transition zone between the sylvo-pastoral and peanut basin, and pastoral area. The variability in annual rainfall is very high in these areas (Joseph *et al.*, 2023; Vieira Junior *et al.*, 2023). In Meouane and Thiel clusters, the onset of the rainy season is around late June to late July and the cessation of rainfall is late September to early October. In the Daga Birame cluster, the onset of the rainy season starts in early June while the cessation of the rainy season is late October. The average seasonal rainfall in Meouane cluster community receives is at least 350 mm in a good year and less than 300 mm in a below-average year. In the Thiel cluster, the annual average ranges between 300 and 500 mm while in Daga Birame cluster the average rainfall ranges between 400 and 600mm. Soils in these zones are mainly sandy of low fertility and seasonally waterlogged or flooded clays (FAO, 1993). They are classified as Lixisol according to FAO (1993) soil classification.

Demonstration trials

Three agricultural innovation technologies were deployed through multi-location demonstration plots during the rainy seasons of 2022 and 2023. This was to evaluate pearl millet varieties' response to variable climate risks and farm management practices and promote best-bet climate-smart management practices for adoption as well seasonal yield forecasting using DSTs- decision-support tools. Therefore, based on the low level of soil fertility at the farm level, integrated soil fertility management (ISFM) such as micro-dosing fertilization approach, and improved variety were demonstrated across 18 villages while promoting improved variety and improved density were implemented in four locations. In each cluster, six villages were associated, and, in each village, four farmers were selected and given a total of 72 demonstration plots. The ISFM technology comprised four levels of organo-mineral fertilizer strategy using micro-dosing techniques namely T_1-150kg of NPK (15:15:15) + 100kg of Urea(46%N), T_2- 150kg/ha (NPK)+ 100kg/ha (Urea) + 2.5ton/ha cow manure, T_3- 75kg/ha (NPK)+ 50kg/ha (Urea) +1.25ton/ha cow manure, T4- 75kg/ha (NPK) + 2.5 ton/ha (Cow manure). Based on these treatments, the quantity of fertilizer per hill was derived. Previous studies by Tabo et al. (2007) and Akinseye et al. (2023)adopted micro-dosing techniques for sorghum and pearl millet in a similar environment. The improved density comprised 25,000 hills ha^{-1} compared to farmers' practice (12,500 hills ha^{-1}) while the improved variety was dual-purpose (SL 28, SL 423, and Thialack 2) compared to farmer's improved local (Souna 3). The demonstration plots followed the randomized complete block design (RCBD) having four fertilizer treatments and two millet varieties, farmers within the same village were used as replications, and each plot size was 63m2 (10 m x 6.3 m) with 7 rows, sown at 0.45m within a row.

Agronomic data

Millet panicles and fodder were harvested at physiological maturity from the three central lines of each plot (7.29 m^2) to avoid border effects. Stover weight was taken after sun drying for 14 days when almost no change in weight was observed between consecutive measurements (Reddy et al., 2010). The yield was extrapolated and then reported on a hectare basis. The panicles were threshed and weighed to determine grain yield. The grain and stover yields from each plot were estimated in kg ha^{-1}. Furthermore, the Harvest Index (HI) was computed to appreciate the efficiency of a crop in converting resources into harvested yield based on each variety and fertilization level. The formula is given:

$$HarvestIndex(HI) = \frac{Grainyield(kg/ha)}{Abovedrymatter(kg/ha)}$$

Statistical Analyses

R software version 4.3.3 was used for statistical analysis. Two-way ANOVA was performed to assess treatment, variety, and year effects on grain and stalk yields as well as on harvest index. The Tukey test at $p < 0.05$ was used for mean discrimination for all the experiments. The analysis was set for each cluster. Furthermore, to assess adaptability, the means, and coefficient of variation were computed.

Results and Discussion

Variety, and Fertilization Effect on Millet Grain, Stover Yields, and Harvest Index

The evaluation of ISFM and improved variety as climate-smart technology under improved density at the farm scale showed no significant ($p > 0.05$) effect of variety, and fertilizer on grain and stover yields and harvest index (Table 1) across the three locations. Despite, no significant effect, the analysis of mean performance emphasized dual-purpose millet variety yielded grain greater than improved local variety for all three clusters over the two years. Therefore, the study highlighted the relative stability of improved local variety giving an advantage for dry conditions meanwhile dual-purpose varieties exhibited an increased yield. This stability of improved local has been noted by Faye et al. (2023) across many environments compared to dual-purpose varieties. The harvest index (HI) showed that the dual-purpose variety recorded a greater value than the improved local variety. This justifies that dual-purpose millet varieties have been chosen to generate high-quality fodder without compromising grain production (Faye et al., 2023; Tounkara et al., 2020). The grain yield increased by 37% (Thiel), 15 % (Meouane), and 8% (Daga Birame) for dual-purpose than improved local variety. Figure 1 displays the overview of this difference. These results agree with Faye et al. (2023) who found improved local variety to be lower yielding compared to dual-purpose millet varieties. Furthermore, the HI of dual-purpose variety recorded slightly greater value compared to improved local. Moreover, the greater value of HI in the wettest location (Daga Birame) explains the relevance of how changes in rainfall patterns can influence the partitioning of assimilates between grain yield and stover biomass, thereby impacting the harvest index. Regarding the micro-dosing fertilizer strategy, in Daga Birame, the HI values for the four treatments were good. In Meouane, the HI of treatments 1 and 4 were greater than others while in Thiel, it was treatments 2 and 4. Globally, when comparing the grain yield to the national average given by FAOSTAT (2021), the increase is by 27% (Thiel), 63 % (Meouane), and 104% (Daga Birame). This finding underscores the importance of adopting smart management practices (high population, micro-dosing) whether smallholder farmers are using landrace varieties or dual-purpose varieties. Tounkara et al. (2023) also highlighted how the use of micro-dosing technology increased grain yield in Senegal by 62% when compared to farmers' practices and by 148% when compared to the control group. Badiane et al. (2001) underlined that in Senegal's semi-arid agroecological zone, millet output significantly increased when farmers applied both mineral and organic fertilizers. They further highlighted that the efficiency of the fertilizer applied was better with the micro-dosing technology than with the recommended rate. Indeed, Hayashi et al. (2008) noted that the application of micro-dosing alone increases millet yield by 56% above the control. But combining with crop residue or manure increased millet grain yield to 140% over the control. These results can explain the importance of combining organic and inorganic fertilizers in micro-dosing technology. The adoption of these practices by farmers can significantly contribute to reducing yield gaps and making more available fodder for livestock.

Table 1: p-value of ANOVA test of varieties and fertilization on millet grain and stover yields and Harvest index in three clusters in Senegal

	Factor	Gain yield			Stover yield			Harvest Index (HI)		
		Daga Birame	Meouane	Thiel	Daga Birame	Meouane	Thiel	Daga Birame	Meouane	Thiel
		Mean			Mean			Mean		
Variety type	Improved local	1800	1454	1265	5538	4883	4501	0.32	0.32	0.26
	Dual-purpose	1941	1664	1501	5610	5218	4585	0.42	0.35	0.32
	LSD (P-value)	282.3^{ns}	210.2^{ns}	345.5^{ns}	630.5^{ns}	383.5^{ns}	686.8^{ns}	0.12^{ns}	0.06^{ns}	0.10^{ns}
	Increase (%)	8	15	37	1	7	2	31	9	23
Fertilizer	T1	1965	1634	1413	5613	5059	4582	0.35	0.35	0.27
	T2	1852	1607	1513	5582	5158	4926	0.35	0.31	0.31
	T3	1897	1474	1459	5638	4925	4410	0.37	0.33	0.29
	T4	1776	1576	1221	5560	5064	4264	0.35	0.35	0.30
	LSD (P-value)	400.9^{ns}	301.1^{ns}	495.2^{ns}	894.9^{ns}	545.6^{ns}	969.7^{ns}	0.17^{ns}	0.08^{ns}	0.14^{ns}

Ns, *, **, and *** indicate that the source of variation was significant at $p < 0.05$, 0.01, and 0.001, respectively

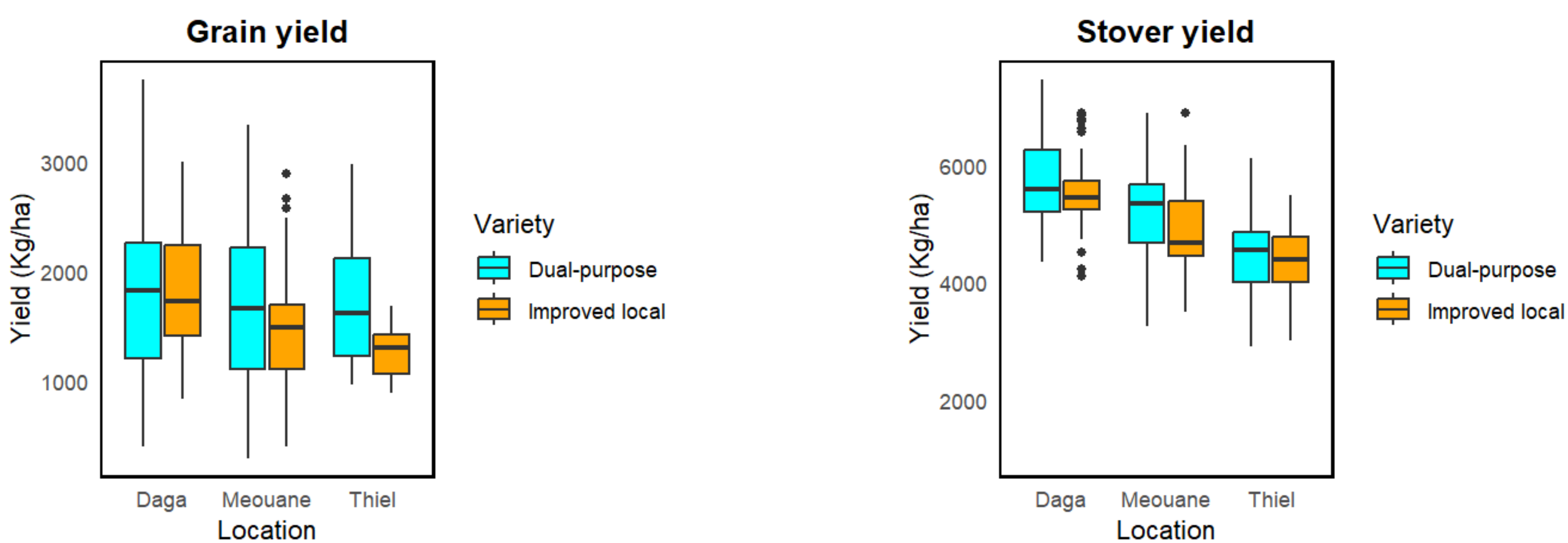

Figure 1: Variety's grain and stover yield performance across the clusters (Daga Birame, Meouane, Thiel) for both years of on-farm experimental trial

Effect of Variety, and Density on Millet Grain, Stover Yields, and Harvest Index

The evaluation of improved density and improved variety as climate-smart technology compared to farmers' practice (low density) emphasized a significant ($p < 0.05$) effect of plant density on grain and stover yields (Table 2) across the three locations while the variety effect was not significant. The grain yield was increased by 53% (Daga Birame), 51% (Meouane), and 56% (Thiel) for improved density compared to farmers' practice (low density). Also, the stover was respectively increased by 55%, 62%, and 64% across the locations. The great performance associated with improved plant density illustrates the importance of optimizing planting density as a smart agricultural practice to enhance yields. This is in line with Faye et al. (2023) and Pilloni et al. (2022) who found that increasing the plant density to 25,000hill ha^{-1} enhance significantly millet fodder and grain yield in Senegal. The performance of high density can likely be attributed to the good vegetation cover associated with higher plant populations, which could reduce evapotranspiration and keep more soil moisture. Across all the locations, even though a significant effect was not found between dual-purpose and improved local millet variety, dual-purpose performed better and increased yield compared to improved local. The HI was slightly greater under improved density and dual-purpose variety compared to farmers' practice even though no effect was found. The effect variety of HI was further significant in the wettest location Daga Birame which highlighted the importance of rainfall patterns for the partitioning of assimilates between grain yield and stover biomass, thereby impacting the harvest index.

Table 2: p-value of ANOVA test of density and variety on millet grain and stover yields and Harvest index in three clusters in Senegal

		Grain yield (kg ha^{-1})			Stover (kg ha^{-1})			Harvest Index (HI)		
		Daga Birame	**Meouane**	**Thiel**	**Daga Birame**	**Meouane**	**Thiel**	**Daga Birame**	**Meouane**	**Thiel**
Density	HD (25,000 hills ha^{-1})	3424	3294	2855	6541	5297	5346	0.35	0.35	0.37
	LD (12,500 hills ha^{-1})	2242	2187	1831	3995	3260	3446	0.33	0.34	0.36
	LSD (P-value)	287.4***	509.3***	575.9**	578.9***	872.8***	749***	0.03ns	0.04ns	0.07ns
	CV (%)	12	19.8	29	13	24.1	20.1	10	20.4	24.2
	Increase (%)	53	51	56	64	62	55	6	3	3
Variety	Dual-purpose	2916	2885	2633	5306	4313	5055	0.35	0.36	0.37
	Improved local	2586	2309	2246	5154	4174	4176	0.31	0.31	0.36
	LSD (P-value)	672.8ns	774.9ns	828.5ns	1460ns	1447ns	1240ns	0.03*	0.04ns	0.09ns
	CV (%)	24.3	26.1	36.2	28.3	34.6	28.9	9.6	18.9	24.3

Ns, *, **, and *** indicate that the source of variation was significant at $p < 0.05$, 0.01, and 0.001, respectively. HD=high density, LD=low density

Conclusion

This study obtained core results that need to be integrated with multi-year agricultural trial data. Our results highlighted the significant effect of improved plant population on grain and stover yields compared to traditional plant populations indicated low density, while there was a slight increase in yield between dual-purpose millet varieties and improved local millet varieties. Adopting smart management practices such as the use of dual-purpose and microdosing technologies and higher plant hill populations have demonstrated increased grain and stover yields at the farm level, therefore significantly narrowing the gap between farmers' yields and potential yields. The PREA further suggests that farmers adopting these smart management strategies would not only exceed the national average but also have the potential to further increase food production. However, future analyses to evaluate the affordability and feasibility of each climate-smart technology used in this study, considering various economic factors such as input costs, market prices, and potential yield increases at each location.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact Assesment of Gully Erosion Hazards Affecting Food Security in Gashala Area, Hong Lga, Adamawa State, Nigeria.

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Abstract

An impact assessment of gully erosion hazards on food security was carried out in ten (10) locations of arable lands in Gashala environs, in the year 2023. The study comprised of measurement of the physical characteristics which include texture, bulk density, porosity, the length, depth and the width of each gully site. The gully volumes were also measured and classified. The result of the physical properties indicated higher sand content relative to Silt and Clay. The textural analysis revealed that the average value for Sand, Silt and Clay were 52%, 27% and 20% respectively; giving a textural class that is predominantly loam. The sandy texture of the soil surface made the bulk density to be high ranging from 1.58 g/cm^3 to 1.74 g/cm^3. This bulk density of the soil surface was high enough to generate surface runoff that favored soil erosion. The results of gully measurements revealed that Milendi was highest in volume (1,020 m^3), Pavu has the longest gully (152 m), Contarabi 3 was deeper in size (5.2 m) and highest area covered by gully erosion (19.2 m^2), Contarabi 2 has the lowest gully volume of 128 m^3, the shallowest depth (1 m) and the least covered area (3.2 m^2). The shortest gully was Contarabi 1 (19 m), the gully was widest at Naiwa (6.2 m). These variation in sizes of length, depth, width, area and volume indicated the impact of several factors of erosion active at the erosion sites. The rate of soil loss ranged from 100.8 t/ha/yr to 561.84 t/ha/yr across the locations, with the highest rate recorded at Pavu. The effects of these soil loss on food security were dual; On-site productivity (loss of crop yield, top soil, nutrient and decline in soil quality) rated as ₦10.5m and Off-site effects (seedling burial, chemical effects, burial of top soil and alteration in soil-water regime and water-table) also rated as ₦07.3m. Literature shows factors may be for gully erosions which may include climatic, anthropogenic, topographic, edaphic and vegetative. Possible biological and engineering measures are also reported in literature. The biological measures of erosion control are basically adopted when the land slopes are smaller than 2% in general, and erosion problems are not severe. When the land slopes are more than 2%, engineering measures may be necessary.

Key Words: Erosion Hazards, Food Security, Arable, anthropogenic, Topographic, Edaphic and Engineering.

Introduction

Soil erosion leads to the removal of soil nutrient and degradation of soil structure, is considered to be a major environmental and social issue affecting the ability of a range of soil functions worldwide (Singh & Panda, 2017). It is considered the most conspicuous and widespread agent of soil/land degradation ever known (Lal, 2015; European Cooperation in Science and Technology (COST), 2008; Kumar & Ramachandra, 2003). It is estimated that 1/6 of global soils has already been degraded by erosion due to water and wind, resulting in a reduced ability of society to produce sufficient food (agriculture) (Wang et al., 2020). The productive power of some lands (worldwide) has declined by half due to the effect of erosion and desertification (Eswaran, Lal, & Reich, 2001). Annually, 75 billion tons of soils are lost from farm lands, and 12 million hectares of cropping land which means approximately 1% of the total area is no longer fit for farming, leading to the degradation of 38% of global cropland since World War II (Dahl, 2013). Soil loss also leads to several other farm challenges, and as these problems increase, there comes a point at which the farm is abandoned (COST, 2008; Anthoni, 2000).

Gullies are defined as "a channel resulting from erosion and caused by the concentrated but intermittent flow of water usually during and immediately following heavy rains; Deep enough to interfere with, and not to be obliterated by, normal tillage operations" (Tarekegn, 2012). Gullies are one of the most destructive forms of erosion, damaging farmland and difficult to reverse (Billi and Dramis, 2001; Moges and Holden, 2009). Gully erosion, especially in semi-arid areas is a burning problem as it leads to degradation of agricultural land (Kropacek *et al.*, 2016). Additionally, gullies tend to evolve head ward thus, increasing the drainage density and accelerate desertification processes in the semi-arid zones (Valentin & alii, 2005). It was also shown that gully erosion is often a major contributor in reservoirs sedimentation, which is a serious problem especially in semi-arid areas with pronounced seasonality in precipitation such as Ethiopia and Nigeria (Hamed & *et al.*, 2002; Haregeweyn & *et al.*, 2006; Tamene & *et al.*, 2006). Usually, gully erosion is triggered or accelerated by land use change and/or by extreme climatic events (Valentin & *et al.*, 2005).

Food insecurity will continue to be a serious issue in coming decades, despite significant projected overall reductions in hunger projected by the end of the century – from the current 850 million to about 200-300 million – many developing countries will continue to experience serious poverty and food insecurity, due to localized high population growth rates, poor socio-economic capacity and continued natural resource degradation. By the end of the century, 40 to 50 percent of all undernourished are expected to live in sub-Saharan Africa (FAO, 2012).

Soil attrition can be devastating to agricultural development and food security (Ighodaro, et al., 2016). It leads to productivity or overall farm yield losses, especially because of decreased fertility of the soil due to loss in soil nutrients. It diminishes the quality of soil through the loss of water, soil organic matter, nutrients, biota, and depth of soil, thus reducing the productivity of natural, agricultural and forest ecosystems (Gundiri, 2023). Further, eroded sediment contains a considerably higher measure of organic matter and nutrients than that of the topsoil from where it is derived (Vahyala et al., 2018). Thus, to attain food security and improvements in livelihoods, especially in the rural areas of Nigeria, soil erosion is no doubt one of the agricultural problems that need to be addressed.

Much of the natural covering for the rangelands has been degraded and indigenous vegetation depleted (through charcoal burning and firewood harvesting) thus leaving ground cover in some areas badly depleted (Vahyala *et al.*, 2018). Approximately 70% of all energy consumed in rural areas are generated from wood fuel thus accelerating the pace of devegetation and land degradation (Gundiri *et al.*, 2023).

The problem of land degradation is widespread within Gashala, which also faces poverty and repeated natural disasters, such as droughts and floods, sediment fills up manmade reservoirs, bleeds agricultural lands from its fertility, erodes away the agricultural lands completely, continuous cultivation under the increased population pressure, roads cut off, economic downturns and generally low agricultural productivity which can only be maintained with artificial fertilizers that in many cases are too expensive and also can be harmful to humans. No matter where they result from-natural or human-induced-climate changes, climate variations affect the resilience of diverse ecosystems and sustain the livelihoods of people living in these zones. Among the problems contributing to land degradation are a lack of knowledge about the nature, extent and severity of the condition, and an inadequacy of tools and methods for assessing, monitoring and managing the situation (Gundiri, 2023).

Although loss of net primary productivity (NPP) is sometimes understood to indicate degradation, losses such as these also result in a corresponding loss of human capital and community breakdown in rural communities, as well as poverty-related social costs and a reduction in ability to invest in preventing degradation.

In this regard, assessment of land degradation at basin level is of pressing importance for policy informed decisions concerning food and water security, environmental integrity, and subnational as well as national strategies for economic development and resource conservation. This study is aimed at assessing the impact of soil erosion hazards on food security and capital development in Gashala area, Hong LG, Adamawa State, Nigeria.

Material and Methods

Location and Size

Gashala is a small village settlement in Hildi District, northeast of Hong LG headquarters, where so much farming, business and educational activities are going on. Hong is located between latitudes 10°00′00′′N and 10°35′00′′N and longitudes 12°35′00′′E and 13°20′00′′E. It has a total land area 2,419.11 km^2 (Bashir and Raji, 1999). Hong local government is sandwiched between six Local Government Areas namely; Gombi, Song, Mubi-North and South, Maiha, and Michika. It is also bounded by Borno State to the North. The Local Government Area is predominantly made up of Kilba people, followed by Marghi. Other tribes in small numbers are Fulani, Hausa, Higgi, Fali, Njenyi among others (Wikipedia, 2015).

Climatic Characteristics

The climate of Hong LG is the Tropical Continental type which is characterised by dry and wet seasons; summer and winter (Iloeje, 1981, Adebayo, 1999). According to Adebayo (2020) and data from GeoNetcast (2015), Hong has a mean annual rainfall ranging between 800-1200 mm with onset usually 10th – 20th May and cessation between 26th September and 26th October.

Geology and Hydrology

The Geology of Hong LGA according to Nigerian Geological Survey Agency [NGSA] (2006) is characterised by a mixture of rock types and minerals as presented on. Most of the area (Hong LGA) is underlain by Magmatite and some Porphyritic Granite especially in the North-Eastern (NE) and Eastern part of the Local Government area. Some medium to coarse granite biotite are also found. The hydrology of the area is dependent on the rainfall pattern and the underground reservoir mostly in areas underlain by sedimentary rock formations. According to Adebayo (1999), the water resources available in the State (Adamawa) including Hong LGA are adequate if utilised properly. The rivers in the area are seasonal in nature. The major streams according to Joshua (1999) are Kwaleta and Dugwaba streams.

Relief and Drainage

The relief of Hong LGA comprises flat, relatively flat and rugged terrain with hills and mountains spread across all the districts. The drainage of the area is a function of the existing relief condition as the streams and rivers originates from the highland areas. The parent materials are heterogonous and comprised predominantly loamy sand, clays and sandy clays of a range of colors (Vahyala, et al., 2018). Which are also predominantly alfisols, luvisols, regosols, leptosols, cambisols, vertisols, and lithosols having lithic and paralithic.

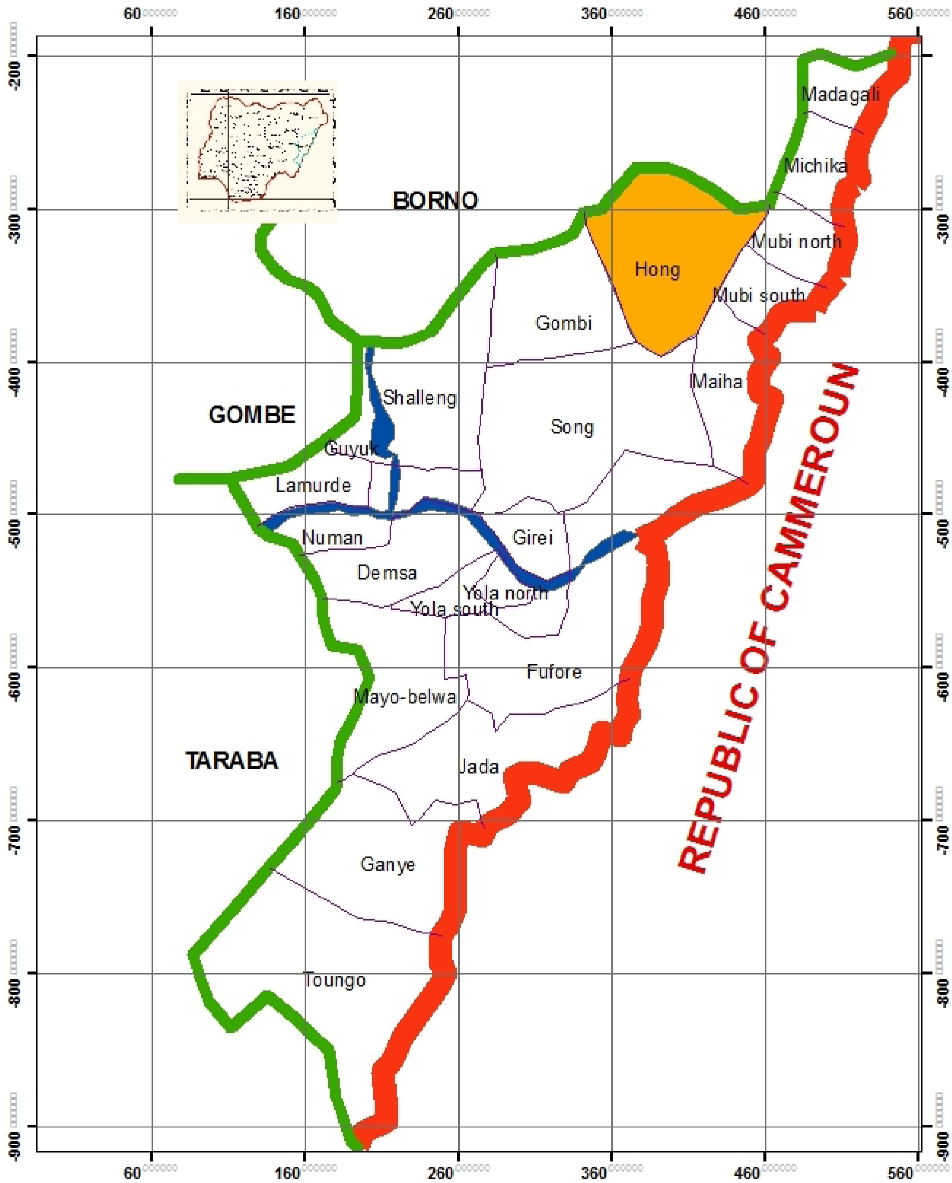

Figure 1: Adamawa State showing the location of Hong LGA (study area)

Source: Adamawa State Government, 2013; Modified by Researcher, 2016

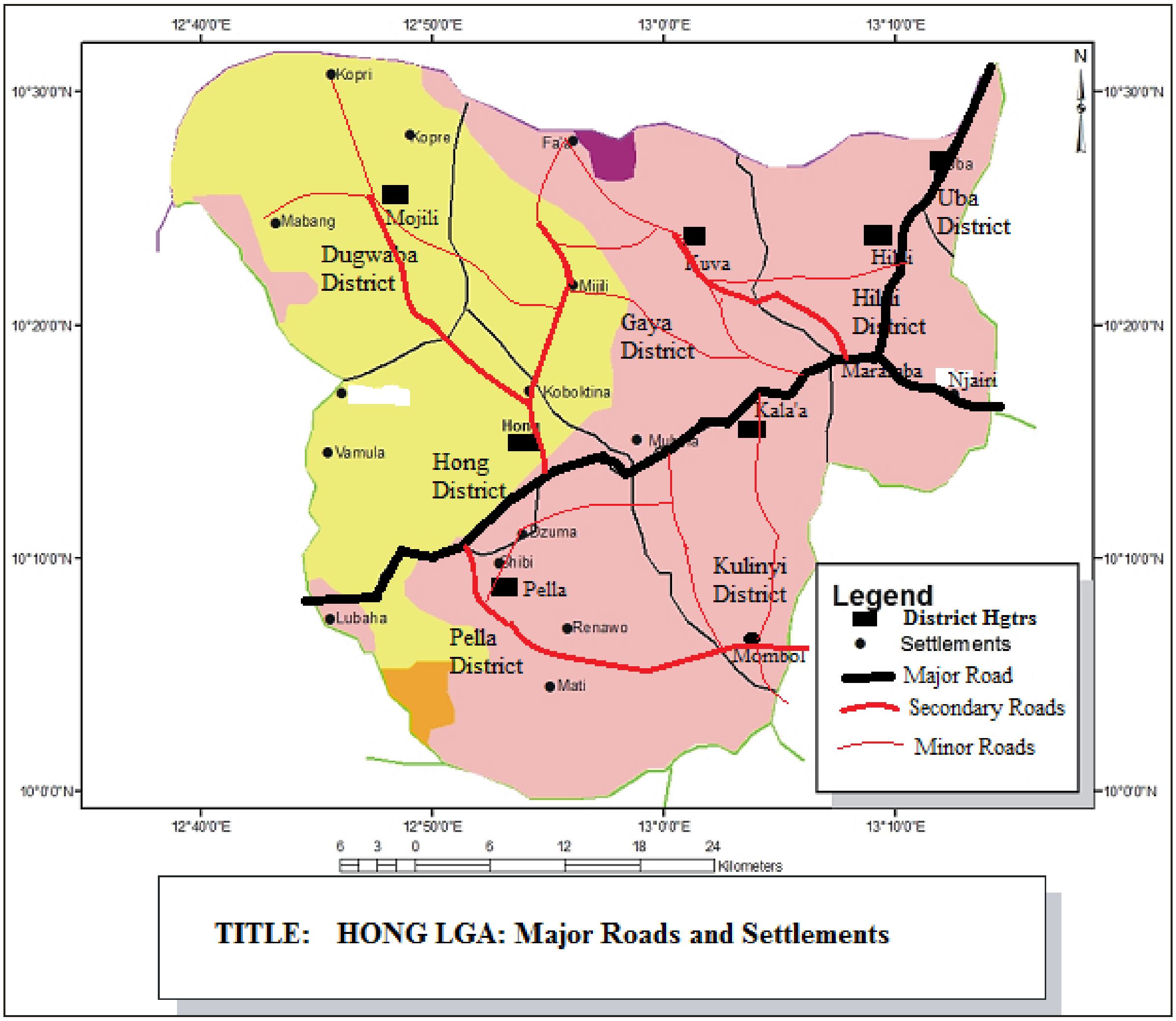

Figure 2: Hong Local Government Area Showing Roads and Settlements

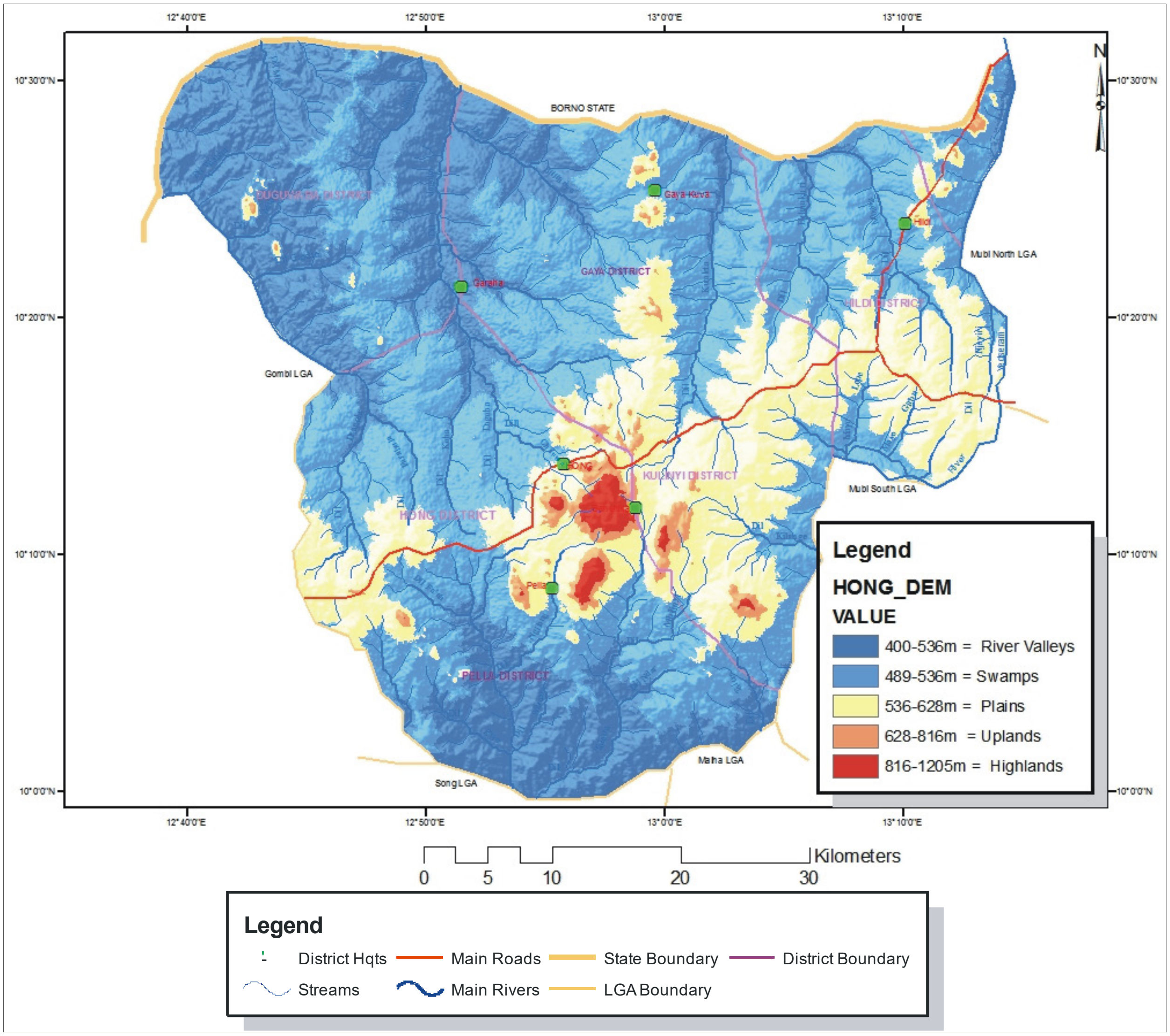

Figure 3: Relief of Hong Local Government Area.

Site elevation and topography

A semi-detailed survey of selected gully erosion sites was conducted in the field in order to develop the digital terrain model (DTM). A global positioning system (GPRS) was used to obtain elevation above sea level of each gully system as suggested by Vandekerckhove et al. (1998), Nachtergaele *et al.* (2001b), and Nasri *et al.* (2008). The study area has a relatively high altitude with the highest reaching 560 m above sea level.

Determination of gully erosion parameters (length, depth, and width)

The following measurements were done in the selected gullies: (1) the head-cut retreat (longitudinal growth) and gully widening (or lateral retreat) downslope from the head-cut, and (2) the gully expansion rates and associated amount of soil loss along the total gully length. To estimate gully expansion and the amount of soil loss from total gully reach, average gully width, depth and lengths were measured using measuring tape at the beginning and end of the rainy season. To determine the soil loss in the various sites were then computed using the measured length (l), width (w), and depth (d) of each gully feature. Thus, actual soil loss estimates were determined using mathematical expressions relating gully length, width, and depth as follows:

Width = (W)

Average width $\frac{(WT+WM+WB)}{3}$ ----------- (10)

Where: WT= Top width, WM = Middle width and WB = Bottom width

Depth = (D)

Average depth = $\sum\left(\frac{(d1+d2+d3+d4+d5+\ --\mp d)}{n}\right)$ ---- (11)

Length = (L)

Where Li is the length of considered gully segment (m)

Cross-sectional area (A)= Average depth*Average width, Gully Volume=A*L --(12)

The gully volume was estimated using the formula: V=ΣLiAi.------(13)

Where Li is the length of considered gully segment (m) and Ai is the representative cross-sectional area of the gully segment (m^2).

Also, after determining all considered factors, the gullies were classified based on gully volume in four groups including big gully (>200 cubic metre), medium gully (volume=100-200 cubic metre), small gully (50-100 cubic metre) and very small gully (volume<50 cubic metre). In addition to this classification, the gullies were also classified based on soil texture as contained in Shahrivar et al. (2012).

Area of soil loss (ASL)

Cross-sectional area (A) = Average width * Average depth

Area of gully = wd ------ (14)

Net area of gully = wd_2 - wd_1 ---- (15)

Where: w = width of gully channel, d = depth og gully channel , w_1 = width of gully channel before seasonal rainfall event, d_1 = depth of gully channel before seasonal rainfall event, w_2 = width of gully channel after seasonal rainfall event, d_2 = depth of gully channel after seasonal rainfall event. The total ASL = Net

Volume of soil loss(VSL)

Gully Volume = Cross-sectional area (A) * Length (L)

The gully volume was estimated using the formula: V= Σ Li Ai ---- (16)

Where Li is the length of considered gully segment (m) and Ai is the representative cross-sectional area of the gully segment (m^2)

Net volume of soil loss (VSL_2 –VSL_1) = Σ $LiAi_2$ - Σ $LiAi_1$ ---- (17)

Where: Li_1 = is the length of considered gully segment before seasonal rainfall event

Ai_1 = is the representative cross-sectional area of the gully segment before seasonal rainfall event

Li_1 = is the length of considered gully segment after seasonal rainfall event

Ai_1 = is the representative cross-sectional area of the gully segment after seasonal rainfall event

The total soil loss volume over the monitoring period will then be obtained by taking the difference in VT after and before the rain phase:

Total VSL = Net VSL -- -- -- -- -- -- (18)

Mass of soil loss

The mass of the soil loss was calculated by multiplying the soil loss volume for each subsection by the measured average bulk density of the soils which was an expression described by Wolf (2003):

Mass of soil loss = Total volume of soil loss (VSL) $_b$ -- -- (19)

Where: δ_b = Soil bulk density

Determination of Rate of Soil loss

Long- and short-term erosion rates were estimated using AGERTIM (Assessment of Gully Erosion Rates through Interviews and Measurements) developed by Nyssen, et al., (2006) was chosen allowing us to understand the historic context of the gully development (Nyssen et al., 2006). As part of this method the watershed area was visited with interviewees as a group and on an individual basis. The field visit allowed the interviewees to recall the changes in the area when they were young.

Long-term gully erosion rates (RL) in tone ha^{-1} yr^{-1} were calculated using the equation:

$$RL = \frac{VBd}{TC} \quad \text{-- -- -- - -- -- --} \quad (5)$$

Where, V= estimated current volume of the gully (m^3), Bd= average bulk density of soils in the watershed, T= Time span of gully development in years, C= the watershed area in hectares.

Short-term erosion rates (Rs) in t ha^{-1} yr^{-1} were determined to estimate the erosion rate in the study period.

$$Rs = (V - V_0)\,\frac{Bd}{TC} \quad \text{-- -- -- -- -- --} \quad (6)$$

Where V= Gully volume at the end of study period, VO=Initial gully volume at the beginning of the study period. T= Time span of gully development in years, C= the watershed area in hectares.

Erosion per unit gully surface (RP), in tone m^{-2} was determined by the formula:

$$Rp = \frac{VBd}{Ap} \quad \text{-- -- -- -- -- -- -- --} \quad (7)$$

Where V= the current volume of the gully, AP= Plane area of the gully (m^2).

Determination of some selected physical soil properties of the study area

Soil texture (particle-size analysis)

The soil texture was determined using the Bouyocus hydrometer method as described by Jaiswal (2003).

The bulk density

The soil bulk density was determined by collecting undisturbed soil sample using soil core sampler, the collected sample was oven dried at 105 C for 24 hrs to a constant weight. The volume of the soil core was determined from the internal radius and the height of the core. The mass of the oven dry soil was divided by its volume to obtain the bulk density of the soil in g/cm^3 (Jaiswal, 2003) in general, bulk densities greater than 1.6g/cm^3 tend to restrict root growth. Sandy soils usually have higher bulk densities (1.3-1.7 g/cm^3) because they have larger, but fewer pore spaces.

$$Bd = \frac{ODM}{V} = \frac{(\pi D^2 h)}{4} \quad (13)$$

Where: ODM = Oven dried mass of sample

V= effective internal volume of container

D= diameter of the container

H= the height of the container

Soil porosity

The porosity of the soil was determined as described by Jaiswal (2003). A particle density of 2.65 g cm^{-3} was assumed. The volume of void spaces found in an oven dry undisturbed soil expressed as a percentage of volume of the soil was termed % total pore

Space. It was estimated by subtracting % solid space from 100. The ratio of bulk density to particle density was a measure of solid space in the soil (Jaiswal, 2003)

$$\%Porosity = \frac{Bd}{Pd}(100) \quad (14)$$

Where: Bd= bulk density

Pd= Particle density

Results and Discussion

Majority of the figures of the bulk density across the location indicated higher bulk density since any value above 1.6g/cm^3 is termed high and can inhibit water infiltration according to Harris, (1990) This indicates a high compaction of the soils in some areas implying the presence of sand concretions that often curtail gully incision at depth of their occurrence. This observation agrees with the reports of Heckmann and Vericate (2018). While the compaction of soils of other location might be the reason of the expansion of those gullies, since compacted sites can cause heavy infiltration inhibition creating favorable condition for ponding and subsequently runoff, and runoff continues rills are formed and later converts to gullies. This is in line with the study of Gundir (2023), which reported that Soils compacted sites, such as animal trails, footpaths, and unpaved roads, can concentrate storm run-off into small areas, thus contributing to gully erosion.

The results of the soil type of the study area indicated high amount of sand relative to silt and clay, which makes it predominantly sandy loam, with few places like; Naiwa 1, Contarabi 2 & 3 which exhibited clay and sandy clay character. These natures of soil in this area may contribute to the erosion of these soils, because soils predominantly sand and sandy loam are mostly prone to washing away due to lack of cohesion, while soils containing clay minerals tend to resist moving water, due to its ability to withstand water pressure. This finding was supported by Githinji et al, (2023), who stated that soils predominantly sand and silt are easily washed away even by low velocity sheet erosion. Also, on the same note, it can also indicate high level of compaction and resistance to erosion, as displayed by sandy clay soil at Naiwa 1 and Contarabi 2.

As observed in (Table 3), all the gully locations were located at the category of the gentle slope (2 – 6%) except for Naiwa 1 falls under moderate slope (6-13%) category. The slope plays a vital role in surface water runoff. For instance, places with high slope have high runoff rate compared to places of relatively flat terrain (Gundiri, 2023). According to the report of Otim et al. (2019) and Idowu et al. (2013) that both runoff volumes and rates increases as watershed size increases; however, both rates and volume per unit of watershed area decreases as the runoff area increases. Watershed size may determine the season at which high runoff may be expected to occur. Due to the nature of the slope rate, gully activities were able to accelerate, because most human activities were carried out at the lower slope, while the streams and rivers originates from the highland areas. According to Idowu et al. (2013), overland flow is the upper reaches of the hydraulic length, shallow flow begins where overland flow converges to form gullies while channel flow is available man-made drains. Also, Githinji et al, (2023) found that as slope are widened, erosion occurs as water flows faster. As a result of this, soil loss increases proportionately to slope length and slope inclination. This finding was in line with this study, because, the slope length and slope incline combined give a good estimate of soil erosion rate, because erosions are caused by surface runoff towards the direction of slope. However, in terms of slope percentage which is the key driver of soil erosion, most areas got a lower percentage hence less susceptible to soil erosion. Consequently, the erosion present were attributed to other factors.

As noticed, higher erosion characteristics and soil loss values (293.71 Kg/ha, 556.72 Kg/ha and 602.67 Kg/ha) for Naiwa 1, Contarabi 3 and Milendi respectively, were recorded at higher altitude areas of Gashala, while the lowest values (195.37 Kg/ha, 87.35 Kg/ha and 71.49 Kg/ha) for Mugau 3, Contrabi 1 and Contarabi 2 respectively, were found at low altitude areas especially where the terrain assumed an almost flat nature. It was noticeable that little variation exists in the altitude of most region within Mugau area. The entire area has a low gradient especially on the lower sides, places like; Mugau, Contarabi 1, Pavu and Naiwa area has got high gradient. This clearly indicate there was some siltation on lower areas.

Where there was no any practice factor that reduce runoff and erosion by reducing the amount of water and the rate at which its runs off, places like Naiwa 2, Mugau and Contarabi that were not cultivated tend to be prone to erosion since they are not subjected to prevention of soil erosion measures.

The erosion per unit gully surface rate (RP) for the 10 gully locations for one year are presented in Table 1. The highest rate was recorded at Pavu with the value of 561.79-ton ha^{-1} yr^{-1}, followed by Milendi with the value of 525.60-ton ha^{-1} yr^{-1}. On the other hand, the lowest rate was recorded at Contarabi1, with value of 64.75-ton ha^{-1} yr^{-1} followed by Naiwa 1 with the value of 100.80-ton ha^{-1} yr^{-1}. The difference in rate of soil loss may be as a result of prevailing factors to be high in other locations more than others. Like, Contarabi 1 was a growing gully with little contributing variables than Pavu which was a sand mining site. Other factors responsible for variation in rate of soil loss was soil type, human activities and altitude.

The pattern of soil loss progress exhibited both increasing and decreasing paths in the various locations for that singular year. The results depict that the rate of soil loss in Gashala area were highest at Pavu and lesser at Contarabi1. These increasing and decreasing pattern may be attributed to the watershed characteristics, soil factors, and Human factors, geologic and climatic factors even as reported by Capra et al. (2004). While, the decreasing pattern were perhaps due to the relative conservation practices such as; vegetative barriers, soil deposition and sand-bag lines, diversion by the water ways to other channels leaving the original flow channel and ridging across the slope direction. As reported by Hailu et al. (2015) that the major soil conservation strategies are broad-based terraces and cover cropping of bare soils. Therefore, conservation practices that address these parameters may be most effective even as reported by Zegeye et al. (2016).

Table 1: Characteristics of The Gully Channel Parameters

S/N	Location & Coord (WGS84: UTM)	Length(m)	Width(m)	Depth(m)	Area (m^2)	Vol(m^3)	BD(Kg/cm^3)	R S L (t /ha/yr)	M S L (Kg/ha)	Vol class	Elev(m)
1	NAIWA 1 0294559 1141437	30	6.2	2	12.4	372	1.6	100.8	210.77	Big Vol	545
2	NAIWA 2 0294536 1141397	90	2.8	2	5.6	504	1.64	311.04	293.71	Big Vol	550
3	MUGAU 1 0293749 1143194	95	3	1.2	3.6	342	1.69	339.72	206.22	Big Vol	535
4	MUGAU 2 0293701 1143226	60	5.5	1.7	9.4	561	1.63	205.92	324.66	Big Vol	501
5	MUGAU 3 0290701 1143226	90	2.4	1.5	3.6	324	1.69	321.84	195.37	Big Vol	501
6	CONTARABI 1 0293707 1143215	19	2	4	8	152	1.62	64.75	87.35	Med Vol	547
7	CONTARABI 2 0291650 1141958	40	3.2	1	3.2	128	1.58	132.48	71.49	Med Vol	560
8	CONTARABI 3 0291677 1141977	50	3.7	5.2	19.2	962	1.63	171.6	556.72	Big Vol	555
9	MILENDI 0293463 1145662	150	3.4	2	6.8	1020	1.66	525.6	602.67	Big Vol	543
10	PAVU 0292937 1145918	152	3.7	1.3	4.8	731	1.74	561.79	455.66	Big Vol	508

Key:

Table 2: Some Soil Physical Characteristics of The Gully Locations

S/N	LOCATION	COORDINATE WGS84: UTM	%SAND	%SILT	%CLAY	TC	BD (g/cm^3)	PD (g/cm3)	%Porosity
1	**NAIWA 1**	0294559 1141437	53.2	20	26.8	CL	1.6	2.61	39.43
2	**NAIWA 2**	0294536 1141397	53.87	25.33	20.8	SL	1.64	2.56	38.28
3	**MUGAU 1**	0293749 1143194	61.7	21	17.3	SL	1.69	2.63	41.5
4	**MUGAU 2**	0293701 1143226	41.2	40	18.4	SIL	1.63	2.61	43.6
5	**MUGAU 3**	0290701 1143226	47.3	32	20.8	SL	1.69	2.58	41.59
6	**CONTARABI 1**	0293707 1143215	50.53	26.67	22.80	L	1.62	2.61	39.93
7	**CONTARABI 2**	0291650 1141958	48.2	25	26.8	SC	1.58	2.5	40.2
8	**CONTARABI 3**	0291677 1141977	47.87	31.33	20.8	SCL	1.63	2.74	43.62
9	**MILENDI**	0293463 1145662	56.7	22	21.3	SL	1.66	2.68	43.11
10	**PAVU**	0292937 1145918	55.87	33.33	10.8	SL	1.74	2.61	41.6

Key: Textural Class = TC, Bulk density = BD and Particle density = PD

Table 3: Some Site characteristics of the Study Area

S/N	LOCATION	COORDINATE WGS84: UTM	Slope	Vegetation	Land use	Probable causes of gully erosion
1	NAIWA 1	0294559 1141437	Moderately sloping (6-13%)	Few grasses & trees	Corn and groundnut	Excessive cultivation, runoff/steep slope
2	NAIWA 2	0294536 1141397	Gently Sloping (2-6%)	Trees, shrubs & grasses	Not cultivated	Landforms
3	MUGAU 1	0293749 1143194	Gently Sloping (2-6%)	Few grasses & trees	Not cultivated	Overgrazing/cattle route
4	MUGAU 2	0293701 1143226	Gently Sloping (2-6%)	Trees, shrubs & grasses	Not cultivated	Indiscriminate road construction
5	MUGAU 3	0290701 1143226	Gently Sloping (2-6%)	Trees, shrubs & grasses	Rice and corn	Excessive land use
6	CONTARABI 1	0293707 1143215	Gently Sloping (2-6%)	Trees, shrubs & grasses	Rice, corn and maize	Excessive cultivation, runoff
7	CONTARABI 2	0291650 1141958	Gently Sloping (2-6%)	Trees, shrubs & grasses	Rice and maize	Excessive land use
8	CONTARABI 3	0291677 1141977	Gently Sloping (2-6%)	Trees, shrubs & grasses	Not cultivated	Excessive land use, runoff
9	MILENDI	0293463 1145662	Gently Sloping (2-6%)	Few grasses & trees	Not cultivated	Minor footpath, runoff
10	PAVU	0292937 1145918	Gently Sloping (2-6%)	Few grasses & trees	Not cultivated	Laterite excavation or Sand mining

Key:

Hazards Assessment

Gully erosion has caused considerable damage to infrastructure like roads, residential buildings, schools and farmlands in Gashala and still posing a serious challenge to other arable lands (Plates 1, 2 and 3). Though, the damages caused by this singular phenomenon cannot be easily quantified, but properties worth millions of naira have been destroyed, animals and human lives has been lost to gully erosion in the study area. However, from the result of study conducted by both interview and measurement (AGERTIM) it showed that 30% of inhabitants of the area have their houses under threat by erosion, while 80% of farmlands in the area are affected by erosion at different stages of development.

An estimated average decline of 35% in farm productivity was observed right from the time the land was put under cultivation to date, due to decline in soil fertility, volume of soil loss and rate of soil loss. The rate at which erosion is going in the area is really alarming. Farms cultivated by my father are no longer cultivated today, my own inherited farmland at Contarabi has been abandoned, because is no longer productive due to erosion. The little farmlands available to us has to be sheared, which poses pressure on the land due to increasing population and hunger. These series of factors have reduced our agricultural income by at least 30% approximately 2-4 million annually.

Out of 20 persons interviewed 2 people each from the gully locations during this research, has lost one or two valuables that amount-ed to one or two million of naira on their farmlands. The approximate total lost was; On-site productivity (loss of crop yield, top soil, nutrient and decline in soil quality) rated as #10.5m and Off-site effects (seedling burial, chemical effects, burial of top soil and alteration in soil-water regime and water-table) also rated as #07.3m.

Other farmers are equally facing the same scenario of losing farmland to erosion, putting pressure on the little left, in so doing, family crises erupt due to lack of land, even to the extent of losing lives as a result of farmers clashes, farmers and herders' crises. So many lives and properties have been lost due to this singular reason of erosion in Gashala directly or indirectly.

Management Strategies

Lack of sensitization programs is one of the key concerns at Gashala, because people are not sensitized about the implication and importance of soil erosion. However, lack of funds to conduct sensitization programs and lack of personnel is also a major hindrance. This clearly indicate that the government and other stakeholders need to increase allocation on soil conservation measures. It was also realized that 30 percent of the sampled population were trained on suitable farming methods while 70 percent were not trained. Suitable farming methods are the key factors to curb soil erosion. Some of the key factors that leads to soil erosion in sandy preferential areas are sand mining or laterite excavation, Indiscriminate construction projects especially roads and overgrazing/cattle route. Gashala is one of the major areas where sand mining and some of these activities are carried out excessively, especially during the rainy season. Majority of sampled population in the area portrayed a zone where sand mining is not regulated. This call for intervention from the government to regulate sand mining. Farms should always be encouraged to be managed properly.

Understanding the controlling factors of gully head mi-gration and lateral expansion of gullies is crucial to design appropriate gully control measures. Retreat rates depended most strongly on the stability of the top soil and the volume of runoff flowing down from the high hill. The longitudinal retreat for deep gullies contributes the most to the volumetric gully erosion in the area. Therefore, regrading the gully head and bank slopes could reduce the occurrence of gravity-induced bank collapse for deep gullies.

Plate 1: Typical farmland been abandoned as a result of gully erosion at Mugau

Plate 2: Road nearly cut off by a gully erosion at Mugau 2

Plate 3: Another scenario of farmland abandoned as a result of gully erosion at Contarabi 3

Plate 4: Gully erosion at early stage of development at Contarabi 1

Plate 5: A typical example of gully hazard where a bridge is about to collapse at Mugau 2

Plate 6: *A farmland left uncultivated due to gully erosion menace; this is also a grazing area. Naiwa*

Plate7: *A typical example of a deep gully >200cm³ that made a farmland unproductive at Contarabi*

Plate 8: A gully erosion site that can no longer be used, as can be seen of cowpea been destroyed.

Conclusion

The problem of land degradation is widespread within Gashala, which also faces poverty and repeated natural disasters, such as droughts and floods, sediment fills up manmade reservoirs, bleeds agricultural lands from its fertility, erodes away the agricultural lands completely, continuous cultivation under the increased population pressure, roads cut off, economic downturns and generally low agricultural productivity which can only be maintained with artificial fertilizers that in many cases are too expensive and also can be harmful to humans. No matter where they result from-natural or human-induced-climate changes, climate variations affect the resilience of diverse ecosystems and sustain the livelihoods of people living in these zones. Among the problems contributing to land degradation are a lack of knowledge about the nature, extent and severity of the condition, and an inadequacy of tools and methods for assessing, monitoring and managing the situation. Minimum soil loss was experienced at Contarabi 1 &2. However, Higher rates of soil loss were experienced at Contarabi 3, Mugau, Milendi and Pavu. This can be attributed to several other factors emanating from environment. Most of the soil loss was experienced within agriculturally productive regions thus showing evidence of the fact that agriculture within Gashala area basically contributes to soil loss. This can be attributed to farmers not professionally managing their land.

As such, a more comprehensive soil conservation method will involve the application of certain hydrological or bioenvironmental processes so as to control the overland flow and excessive runoff. Therefore, to prevent, control or reduce all the damages due to soil erosion, the best way to combat in each area, identification of the factors which affect soil erosion as the first measure

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Impacts of agro-ecological practices on soil health and sorghum yield as influenced by climate change in the Sudan-Sahelian zone of Burkina Faso

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Abstract

Drought and low soil fertility remain constraints to agricultural production in Burkina Faso. Agro-ecological practices like stone rows (SR), *zaï* (Z), and ridge tillage (RT) are pointed out as climate-smart alternatives to cope with these challenges. This study aimed to determine the influence of SR, Z, *zaï* combined with stone rows (Z_{SR}), and RT on the soil health and sorghum productivity. The experiment was set up in a randomized complete block design, with four treatments and five replications. Measurements were carried out on soil parameters and sorghum yield components. The results showed that SR, Z, Z_{SR} increased soil moisture content by 5.73%, 23.16%, and 23.55%, respectively, compared to RT. SR, Z, Z_{SR} increased soil carbon, nitrogen, and phosphorus content and pH values. SR, Z, and Z_{SR} increased grains yield by 130%, 271.36%, and 268.57%, respectively, compared to RT. Straw yields were increased by 6.78%, 93.29%, and 66.30% by SR, Z, and Z_{SR}, respectively. The 1000-grains weight was increased by 7.08%, 16.23%, and 16.01% by SR, Z, and Z_{SR} compared to RT. However, SR improved soil respiration with the mean accumulation of 2235 ppm. RT and SR influenced the termites' development. The interrow of *zaï* influenced the ants' development. SR positively influenced the development of earthworms. To boost sustainable agricultural production, we should think about mechanization and dig new *zaï* annually to increase the ability of *zaï* and stone rows to restore degraded soils in the Sudan-Sahelian zone of Burkina Faso.

Keywords: Agro-ecological practices, soil fertility, *zaï*, ridge tillage, stone rows.

Introduction

World cereal production was estimated at 2.7 billion tones in 2022 - 2023. Sorghum currently ranks fifth. Sorghum comes 4th in Africa after Sudan, with production of 2.01 million metric tons in 2022-2023 (USDA, 2024). In Burkina Faso, cereal production was 5179,000 tons in 2020, with 1839570 tons of sorghum, i.e. 35.52% of national production (MARAH, 2022). Sorghum production, however, is subject to constraints such as soil nutrient deficiency (Somda et al., 2017), inappropriate agricultural practices combined with climate change (Doumbia et al., 2020), poor fertilization (MARAH, 2022), land degradation and farmers' low income. This situation is keeping sorghum yields below potential. To overcome these production challenges, approaches and good agricultural practices have been developed and disseminated to farmers. These approaches and techniques aim to contribute to the sustainable intensification of production and preservation of soil fertility through the restoration of soil quality: integrated landscape management, integrated soil fertility management, integrated pest management, *zaï*, stone rows, half-moon, grass strips, different types of ploughing, agroforestry's techniques etc.. Several studies have highlighted the positive impacts of the *zaï*, stone rows and ridge tillage techniques on soil chemical and physical properties, and on crop yields (Ndiaye Saliou, 2009; Amede *et al.*, 2011; Zougmoré *et al.*, 2014a; Partey *et al.*, 2018). These techniques significantly improve soil structure, crop yields, groundwater recharge, and rainfall infiltration (Zougmoré *et al.*, 2005; Kabore-Sawadogo *et al.*, 2013). Indeed, results of Klik *et al.*, (2018) indicate that stone rows are able to increase water infiltration into the soil by 15%, and the results of Zougmoré *et al.*, (2004) confirmed a reduction in runoff from 45% to 53% following the installation of stone rows. In addition, *zaï* combined with organic manure can double or triple sorghum yields and improve chemical properties of the soil, such as pH and organic matter content (Gnoumou *et al.*, 2017; J. Ouedraogo *et al.*, 2021), in Burkina Faso. Though, the effects of them on soil biological properties are not most investigated. Such, the impacts of their combination on soil biological, chemical, and physical properties remain few studied. Thenceforth, the depth investigation will be needful. So, research should focus on combining these practices to sustainably improve cereal yields and the soil's triple property in climate change. This study is based on the hypothesis that *zaï*, and *zaï* combined with stone rows can increase grain and straw production in sorghum. This study aims to determine the influence of *zaï*, stone row and the combination of *zaï* and stone row on the biological, chemical, and physical properties of the soil and sorghum yield parameters in the Sudan-Sahelian zone of Burkina Faso.

Material and methods

Site characteristics

The study was carried out over two cropping seasons from 2021 to 2022 in *Sandogo* (figure 1), in the province of *Kourweogo* in the Plateau Central region. The rainy season mainly covers the months of June to September with an average rainfall of 729.98 mm for the last ten years (2011-2020) and is characterized by interannual variability. The total rainfall was 602.8 mm with 43 days in 2021 and 708 mm with 37 days in 2022. The highest rainfall was recorded in August 2021 (231.8 mm) and September 2022 (291.5 mm). The rainfall recorded in both years is below the average of the previous decade. In 2022, the total rainfall was higher than 2021. The type of soil is indurated leached tropical ferruginous soils and leached tropical ferruginous soils with stains and concretions.

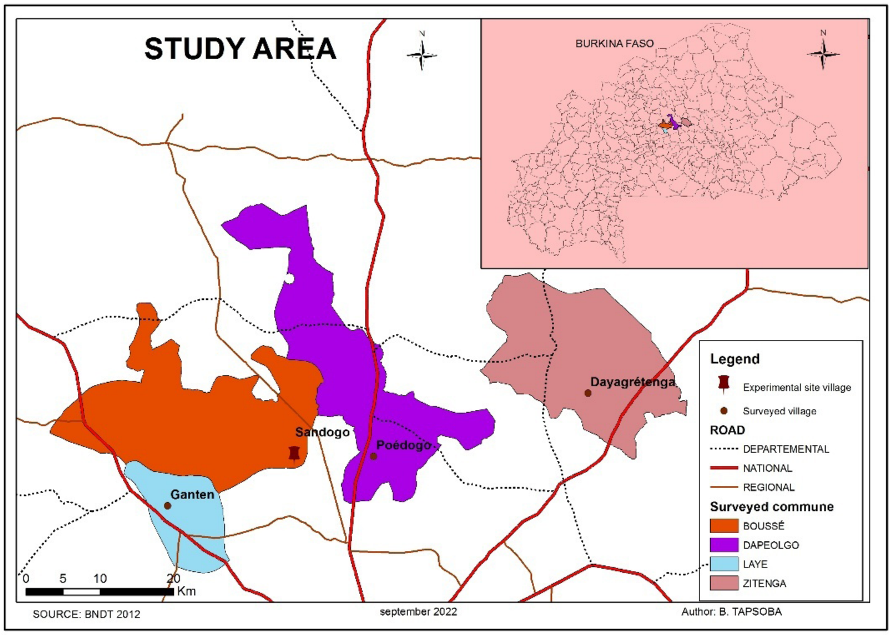

Figure 1. Study experimental site localization.

Experimental design

The experimental design was a randomized Fisher block with four treatments and five replications. The treatments were composed of Ridge tillage as a control (RT), *Zaï* (Z), Stone Rows (SR), *Zaï* + Stone Rows (Z_{SR}). Stone rows are anti-erosion works consisting of a judicious arrangement of stones on contour lines. One line was built in each treatment. Each stone row consisted of two rows of stones placed in a furrow. The upslope row of large stones were stabilized by the downslope row of small stones. Each stone row is about 0.2 to 0.3 m high. The *zaï* is 15 cm deep and has a diameter of about 20 cm.

Agronomic management

The *zaï* pits and the stone rows have been implemented in June 2021. The organic manure was applied in the first year of the experiment at a dose of 5,000 kg. ha^{-1}. The same *zaï* pits were used in 2022. Sorghum was sown on 15 July 2021 and 24 June 2022 at 0.8 m x 0.4 m spacing and thinned at two plants per hill, i.e. 62,500 plants per hectare at a rate of 8 kg. ha^{-1}. The treatments were applied on plots of 20 m x 3.5 m size separated at intervals of 1 m x 10 m. The fertilizer NPKSB was applied 21 days after sowing (DAS) in microdose, i.e. 2 g/hole. The supplementary urea (1 g/hole) was applied on day 45 after planting. Weeding was done manually. Sorghum harvesting was done 105 DAS in 2021 and 105 DAS in 2022.

Data collection

Weather

The total monthly rainfall data for the 10-years average were obtained from weather stations closest to the site. All weather stations were within 20 km of the site, and during the experiment, a rain gauge was positioned in the village of *Sandogo* to collect rainfall data.

Soil sampling and analysis

Description of pedological pit: A field investigation was conducted, based on both pedological trench description and sampling. For pedological trenches, soil descriptions and classification were conducted following the guidelines for soil description by the FAO and adapted by BUNASOLS to the agro-climatic conditions of Burkina Faso. Four soil samples were collected in each pedological trench according to the horizon (one composite sample per layer) for laboratory analysis in order to obtain additional data on the initial soil characterization.

Soil moisture content: From the fortieth day after sowing, surface moisture was measured using a portable moisture meter (IMKO Model HD2 probe moisture meter, Germany). Three moisture measurements were done in each elementary plot in the 0-20 cm soil layer. The measurements were made in five successive times, which are 40 DAS, 50 DAS, 60 DAS, 70 DAS, and 80 DAS.

Soil macrofauna: It was realized 68 DAS in 2021 and 60 DAS in 2022 using Tropical Soil Biology and Fertility method (Ingram and Anderson, 1993) and modified. A metal frame measuring 25 cm x 25 cm x 30 cm is driven into the soil. A monolith is removed, broken up, crumbled, and excavated by hand on a tarpaulin in order to collect the macrofauna, which is stored in flasks containing 75% alcohol. Macroinvertebrates were identified and counted under a binocular magnifying glass using reference books and dichotomous keys (Bouillon & Mathot, 1965; Chinery et al., 1987). The individuals' number in each group was recorded and their weights were done using precision electronic scale.

Soil respiration: it was made by using an IRGA respirometer. Measurement was carried out according to the protocol: 3 soil samples are collected in each plot at 0-10 cm depth. For each plot, individual samples are mixed to make composite sample. The soil samples were air dried and sieved to 2 mm. 2g of soil were placed in glass anticoagulant tubes (3 replicates), brought to optimum humidity, and then the tubes were sealed. They are then incubated in the dark at room temperature. After 2 hours of incubation, the first measurement of CO_2 release is carried out, then the tubes are returned to darkness. The second measurement was after 24 hours of incubation. The other measurements are carried out every 72 hours (twice) to 96 hours of incubation (twice) for 2 weeks.

Soil Texture was determined through the study of the granulometric fractions (3 fractions) which was determined by the international Robinson pipette method. Soil pH was measured with a glass electrode using a 1:2.5 soil to water ratio by (AFNOR, 1981) method. Soil organic carbon (SOC) was determined by (Walkley & Black, 1934) method. Soil total nitrogen (N) was determined by Kjeldahl method taken back by (Novozamsky et al., 1983). Soil available phosphorus was measured by Bray I method (Bray & Kurtz, 1945). The method for determining the cation exchange capacity (CEC) is based on extraction with 0.01 M thiourea silver. It also determines the exchangeable bases (Bunasols, 1987).

Plants data collection

Grain and straw yields of a plot are the yields of all the plants in the useful plot (35.2 m^2). The useful plot is obtained by eliminating two crop lines on each side of the elementary plot to avoid border effects. Their yields are computed taking into account all sorghum plants in the useful plot at harvest. Aliquots of fresh biomass were taken and transported to the laboratory; they were weighed, air-dried for a fortnight and then reweighed to obtain the quantity of dry matter with a constant weight. This value was used as the basis for calculations to obtain the average yields in $t.ha^{-1}$ per treatment. A precision scale was used to determine the weights of one thousand sorghum grains.

Statistical analyses

The plants and soil data obtained were subjected to analysis of variance (ANOVA) using R software (version 4.2.1) at 5% threshold. The Student Newman-Keuls test is used to perform comparisons of means.

Results

Characteristics of the soil

Based on the descriptions of the open soil profile, indurated leached tropical ferruginous soil, and leached tropical ferruginous soil with stains and concretions have been identified. This soil belongs to the class of soils with iron and/or manganese sesquioxide (CPCS, 1967). The soil is 120 cm deep (Figure 2). The colour is yellowish brown (10 YR 5/6) when wet in the first 17 cm, and brownish yellow (10 YR 6/8) when wet over 17-43 cm. These soils are also reddish yellow (7.5 YR 6/8) when wet over 43-84 cm and dark brown (7.5 YR 5/6) in the last 84-120 cm. Dark brown oxidation stains (10 YR 5/8) are visible at depth (43-120 cm). Their rate varies between 10 and 15%. The texture is silty-sandy (Table 20) on the surface (17 cm), silty-sandy-clay (17-43 cm), and silty-clay (43-84 cm) at depth and clayey beyond (84-120 cm). We observed some iron gravel on the first 84 cm as well as iron and manganese concretions (15%) in the last 36 cm. Drainage is imperfect. The structure is weakly developed with subangular polyhedral aggregates throughout the profile. The consistency is friable to very firm from surface to depth. Roots are numerous in the surface horizons and few at depth. There are numerous pores at the surface and few at depth. Biological activity is well developed at the surface and poorly developed at depth. The organic matter (OM) content is low (0.32-0.77%) throughout profile. OM is highly mineralized (C/N= 9-11). The cation exchange capacity is low (4.86-6.45 $cmol^{+}.kg^{-1}$). The sum of exchangeable bases is low (2.87-3.77 cmol+.kg-1). The base saturation is relatively average (51-59%). The soil has a low level of nitrogen (0.02-0.04%), and low levels of available phosphorus (1.10-1.79 ppm). The soil is strongly to moderately acidic (4.87-5.8) with an average cumulative carbon dioxide release of 2676.67 ppm in 2021.

Figure 2. Soil profile of the experimental site

Effects of zaï, stone rows, and ridge tillage on soil moisture content

Soil moisture content significantly varied along the treatments ($p<0.0001$). Moisture levels ranged from 33.67 ± 1.94 to 41.60 ± 1.55 on day 60, from 33.07 ± 1.48 to 38.67 ± 1.18 on day 70, and from 30.60±0.98 to 37.67±0.67 on day 80. The SR, Z, and Z_{SR} treatments significantly improved moisture content compared to the RT. These improvements were +5.73% under SR, +22.16% under Z, and 23.55% under Z_{SR} on 60 DAS, + 0.39% under SR, +16.33% under Z and +16.93% under Z_{SR} on 70 DAS, and +5.46% under SR, +23.10% under Z and +22.87% under Z_{SR} on 80 DAS. The *zaï* and *zaï* associated with stone rows had a greater impact on the variation of moisture levels in soil under Sorghum cultivation. The ridge tillage and stone row treatments recorded the lowest moisture content levels. Moisture contents varied downwards from 60 DAS to 80 DAS, but treatments including *zaï* always remained wetter than treatments consisting only of SR and RT.

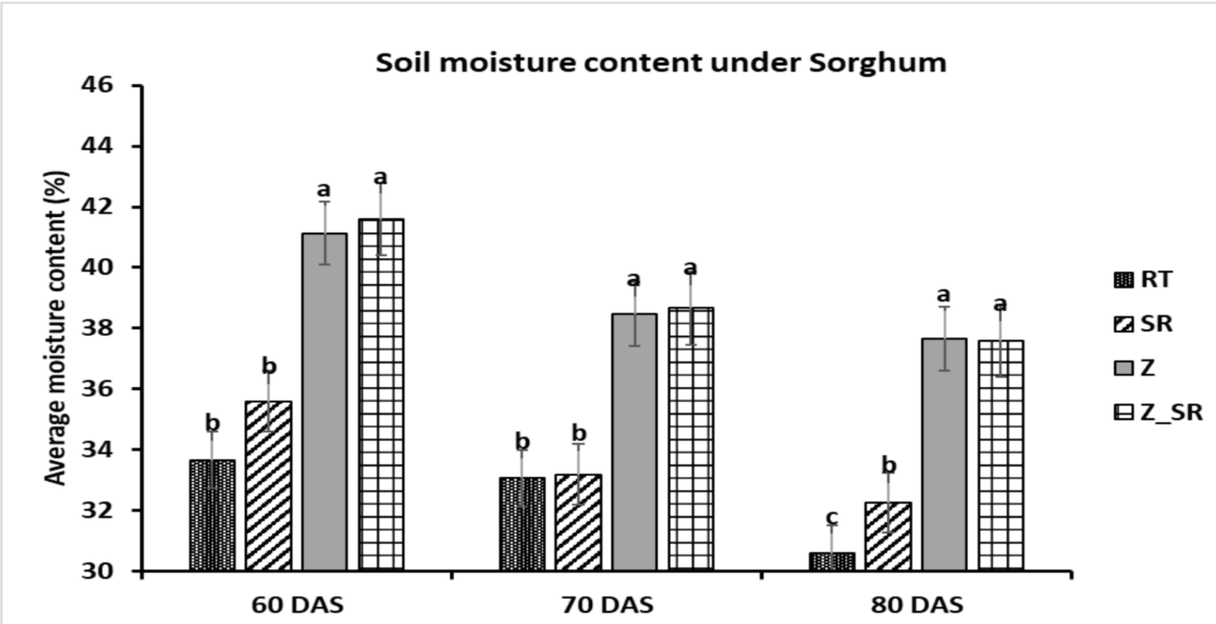

Figure 3. Soil moisture content variation (RT = Ridge tillage; SR = Stone rows; Z = Zaï; Z_{SR} = Zaï + Stone rows; The histograms correspond to the means; the means with same letter do not differ significantly at the 5% level; n = 5; DAS= Days after sowing)

Effects of stone rows and zaï on soil carbon dioxide release variability

The treatments significantly influenced soil CO_2 release. Analysis of variance reveals two homogeneous groups with SR treatment recorded 4070 ppm and occupied the first group (Table 1). The second group is made up of the RT, Z, and Z_{SR} treatments, which recorded 2965.3, 2978.7, and 2924 ppm respectively.

Table 1. Dynamic of soil carbon dioxide release under sorghum

Treatment	CO_2 Release (ppm)	
	2021	2022
RT	2965.3 ± 83.32b	1819.47 ± 55.94b
SR	4070 ± 61.96a	2235.33 ± 43.94a
Z	2978.7 ± 45.62b	1829.33 ± 25.97b
Z_{SR}	2924 ± 69.58b	1804.67 ± 17.73b
P-value	0.0001	0.0001
Signification	***	***

RT= Ridge tillage, SR= Stone rows, Z= Zaï, Z_{SR}= Zaï associated with Stone rows. n=5; means with the same letter are not significantly different at threshold 5%

Effects of stone rows and zaï practices on soil macrofauna variability

In 2021, the Shannon diversity index showed that Z had the richest macrofauna community with IS = 2.0059. This treatment was followed by the SR, RT, Z_{SR} treatments with IS values of 1.9587, 1.7591, and 1.7507 respectively. In 2022, RT had more macrofauna diversity with IS = 2.3706. It was followed by the Z_{SR}, Z, and SR treatments with values of 2.2489, 2.0802, and 2.0146 respectively. Three species of earthworms belonging to the order Haplotaxida, family Octochaetidae (*Dichogaster affinis*), Acanthodrilidae *(Milsonia inermis)*, and Lumbricidae *(Lumbricus terrestris)* were found. In 2021, RT and Z_{SR} treatments recorded the highest number of termites. *Microtermes upembae*, and *Microtermes* sp. are the most encountered species. In 2022, RT and SR treatments had more termites than the Z and Z_{SR}. *Microtermes upembae*, *Macrotermes* sp, and *Microtermes* sp were the most encountered with a total of 227, 99, and 38 respectively. As for ants, eight (8) species were inventoried. In 2021, RT and Z_{SR} treatments recorded a many ant. In 2022, Z and Z_{SR} recorded more ants than RT and SR. *Camponotus pennsylvanicus*, *Monomorium pharaonis*. *Pogonomyrmex* sp., and *Camponotus* sp were the highest number of encountered with total values of 109, 99, 64, and 42 respectively. About earthworms, 3 species were inventoried: Dichogaster affinis, Milsonia inermis, and Lumbricus terrestris. In 2021, SR, Z, and Z_{SR} treatments recorded earthworms with identical numbers. In 2022, SR and Z treatments stimulated the development of many earthworms. *Dichogaster affinis* and *Milsonia inermis* were mostly encountered with total values of 128 and 54 respectively.

Effects of ridge tillage, stone rows, and zaï on soil chemical properties

The results shown three statistically homogeneous groups (Figure 4). Z and Z_{SR} form the first group. The second group contains the SR treatment and RT represents the third group. Treatments significantly influenced total carbon ($p<0.0001$), total nitrogen ($p<0.0001$), and available phosphorus ($p<0.0001$) contents, and pH values ($p<0.0001$). The highest carbon, nitrogen and phosphorus contents and pH values were found in the zaï (C = 0.572%, N = 0.053%, P = 5.860ppm, pH = 5.77), and *zaï* + stone rows (C = 0.580%, N = 0.053%, P = 5.980 ppm, pH = 5.80) treatments followed by the SR (C = 0.436%, N = 0.045%, P = 3.316 ppm, pH = 5.51) treatment. The lowest nutrients content and pH values were observed in the RT (C = 0.297%, N = 0.033%, P = 2.016 ppm, pH = 5.25) treatment. Z, Z_{SR} and SR treatments significantly improved Carbon (C), Nitrogen (N), available phosphorus (P) and mean pH values of soils collected at harvest compared to RT treatment.

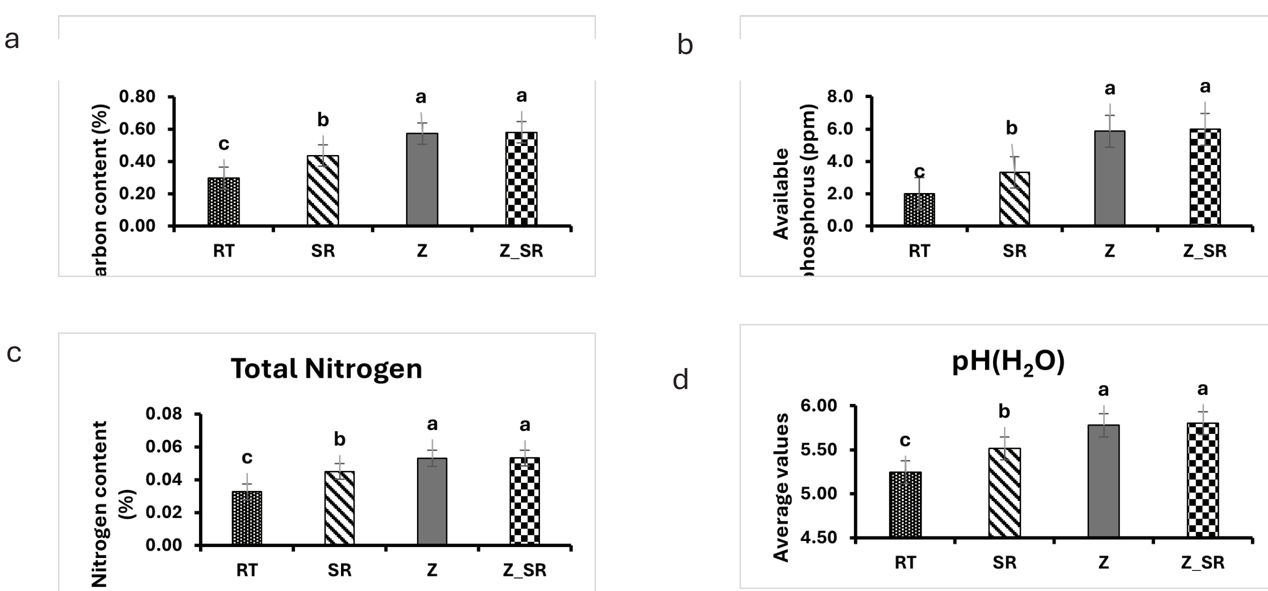

Figure 4. Effects of treatment on C (a), P (b), N (c) content, and pH (d) values. (RT = Ridge tillage; SR = Stone rows; Z = Zaï; Z_{SR} = Zaï + Stone rows; The histograms correspond to the means; the means with same letter do not differ significantly at the 5% level; n = 5)

Effects on the grains and haulm yields and 1000 grains weight.

Grain yields were significantly increased in 2021 ($p<0.0001$) and 2022 ($p<0.0001$) under SR, Z, and Z_{SR} treatments compared to RT (Table 2). In 2021, this increase was 36.57% by SR, 337.48% by Z, and 332.67% by Z_{SR}. However, in 2022, this increase was 130% by the SR, 271% by the Z, and 268% by the Z_SR. In 2021, the increase in 1000 grain weight was 6.39% by SR, 22.02% by Z, and 17.09% by Z_{SR}. In 2022, the increase was 7% by SR and 16% by Z and Z_{SR}. The same trend was noted in straw yields by all three treatments and in both seasons. Thus, SR stimulated an increase of 10.99%; Z by 139.84%, and Z_{SR} by 92.74% compared to RT in 2021.

Table 2. Effects of treatments on grains yields, straw yields and 1000-grains weight

Treatment	Grains Yield ($kg.ha^{-1}$)		Straw Yield ($kg.ha^{-1}$)		1000-GrainsWeight (g)	
	2021	2022	2021	2022	2021	2022
RT	380.38±9.67c	467.55±8.22c	2038±719.81c	2920±783.96b	19.40±0,97b	18.48±1.55b
SR	519.47±8.99b	1075.06±14.32b	2262±688.60c	3118±1012.73b	20.64±1.50b	19.79±0.81ab
Z	1664.01±23.46a	1736.32±11.53a	4888±507.81a	5644±631.29a	23.67±2.14a	21.48±1.34a
Z_{SR}	1645.77±20.86a	1723.28±15.85a	3928±895.08b	4856±907.02a	22.74±1.13a	2.44±0.81a
P-value	0.0001	0.0001	0.0001	0.0002	0.0014	0.0023
Signification	***	***	***	***	**	**

Discussion

Effects on soil carbon, nitrogen, available phosphorus, and pH

The C, N, and P content of soils under sorghum was improved under Z, Z_{SR}, and SR compared to soils under RT. According to our study, the Z, Z_{SR}, and SR treatments increased organic carbon, total nitrogen, available phosphorus, and pH values. This increase in carbon would be due to the addition of cattle manure at the time of establishment and to the return of a small part of the plant through the roots, as they are the main carbon depositor in the soil (Allmaras *et al.*, 2004; Wilhelm *et al.*, 2004). Moreover, some authors found that the roots of sorghum can accumulate up to 14% of the total carbon capture in the above-ground and below ground biomass (Andress, 2004; Wilhelm *et al.*, 2004). According to the study by (Cai *et al.*, 2019), the application of manure promotes the increase of soil organic carbon contents, pH, and nutrients content. Therefore, we can conclude that zaï associated with cattle manure and the return of sorghum roots contribute to increasing soil carbon content. Soil N levels were also improved under Z, Z_{SR}, and SR compared to those sampled under RT. This result is logical due to the urea supply and the return of roots coupled with the increase in organic matter in *zaï*. Indeed, organic matter reduces the inflow rate and improves the soil's water retention. This retention avoids the nitrogen transport in depth by water (Fatondji *et al.*, 2011). Available phosphorus levels are higher under the Z, Z_{SR}, and SR treatments compared to the RT treatment. These treatments are therefore beneficial to the improvement of the soil's available phosphorus content. These results corroborate those of Getare *et al.*, (2021) who found that *zaï* combined with manure increased the levels of soil available phosphorus content. In our case, this improvement in available phosphorus levels is attributable to the interaction of *zaï*, manure, and NPK mineral fertilizer. Indeed, soil amendment by the application of manure improves the physicochemical properties of the soil and the nutrient cycle by reinforcing the enzymatic and microbial activities of the soil. This will trigger the process of bioavailability of phosphorus for plant uptake (Ali *et al.*, 2019) and provide phosphorus in the soil through the content of inorganic orthophosphates in manure. Z, Z_{SR}, and SR treatments stimulated higher pH values than RT. This dynamic is similar to that of carbon, nitrogen, and available phosphorus. Thus, Z, Z_{SR}, and SR treatments positively influence the improvement of soil acidity. The higher pH values under these treatments could be attributed to the manure that increased the organic matter content of soils. However, alkalinity of organic matter as a result of the decarboxylation of organic anions and ammonification of organic nitrogen stimulates the increase of soil pH and neutralizes its acidity (Rukshana *et al.*, 2014; Cai *et al.*, 2019).

Effects on soil moisture content

Our results showed a significant increase in soil moisture content under *zaï* and *zaï* associated with stone rows, confirming the key role of *zaï* pits in improving soil water retaining capacity on degraded soils. Indeed, the highest moisture levels were recorded on soils under zaï and under zaï associated with the stone rows. This is because the *zaï* pits collect water and retain moisture. The addition of organic manure would increase soil organic carbon content, which improves porosity and water holding capacity (Annabi et al., 2011) and contribute to conserve soil moisture content. In the SR treatment, even with ridging, moisture levels remain lower in the *zaï*. This suggests that even with organic fertilizer and ridging, which should reduce water transport of fertiliser, zaï pits would be more efficient in storing and retaining water.

Effects on soil respiration

A significant cumulative release of CO_2 was obtained on soil under SR. This is due to the application of organic fertilizer. The organic manure increases the organic matter content and raises the soil pH. However, pH and organic matter influence the biological activity of the soil. In addition, tillage such as flat plowing and ridging would contribute to lowering the soil bulk density (Serme *et al.*, 2015). This situation is manifested by an improvement in soil moisture and aeration, thus inducing a good development of microorganisms. Then, the mineralization of organic matter will be accelerated, and the amount of CO_2 released will depend on the microbial population, their diversity, and the metabolic enzymes secreted.

Effects on soil macrofauna dynamic and diversity

RT, SR, and Z_{SR} treatments recorded more termites than the Z treatment. The presence of mushroom termites could be explained by the contribution of manure. cow dung manure is a lignocellulosic biomass (Ashekuzzaman & Poulsen, 2011). However, according to some authors (Maldague, 2005; Zaremski *et al.*, 2009), termites feed mainly on cellulose. Furthermore, this situation could be explained by the adaptability of termites, which is sometimes favored by the symbiotic relationship they maintain with certain fungi, facilitating the degradation of food (Guedegbe *et al.*, 2008). As for the ants, Camponotus, Monomorium, and Pogonomyrmex are mostly represented. The genera Messor and Formica were the least encountered. This leads us to hypothesize that the combination of soil management techniques, manure, and mineral fertilization, soil type, and crop provides a favorable environment for ant populations. The application of treatments on sorghum was also favorable to the growth of earthworms. The species recorded are anecitic *(Dichogaster affinis* and *Lombricus terrestris*) and endogenous *(Millsonia inermis)* worms. The most common species is *Dichogater affinis* followed by *Milsonia inermis. D. affinis* feeds mainly on soil taken from the 0-10 cm horizon and sometimes deeper, while Milsonia inermis feeds on organic fractions taken from the soil at a depth of 30 cm where they live. The presence of this earthworm population could be explained by the incorporation of manure (Traore *et al.*, 2012). Thus, our results let us know that the treatments associated with the type of soil and the culture stimulate good development of the engineers of the soil, which are the termites, the ants, and the earthworms. However, the conditions are better for termites and ants than for earthworms. This leads us to hypothesize that the existence of ants is an obstacle to the development of termites or earthworms. Also, the number of individuals of three soil engineers remained higher in 2022 than in 2021. This can be explained by soil moisture. Indeed, soil moisture stimulates the appetite of invertebrates.

Effects of zaï, stone rows, and ridge tillage on agronomic parameters of sorghum

The results indicated that Z, Z_{SR} and SR treatments had significant effects on grain yields, straw, and thousand grain weight compared to RT treatment. Our work corroborates several authors (Saba *et al.*, 2018; Y. Ouedraogo *et al.*, 2020) and confirms key roles of *zaï*, stone rows and microdose as well as their association on the physical, chemical, and biological fertility of the soil significantly impacting sorghum yields and growth. Indeed, *zaï*, stone rows, *zaï* combined with stone rows and manure reduces runoff, reduces evaporation, facilitates infiltration, improves water retention capacity, and concentrates organic matter (Zougmoré *et al.*, 2014b) and thus improves crop growth and development, increasing grain yields and water and nutrient use efficiency. Furthermore, Z and Z_{SR} treatments gave significantly higher yields than SR and RT. This is because *zaï* pits and stone rows along the contour lines collected water and fine soil and reduced runoff, thus improving soil moisture (Fatondji *et al.*, 2009). However, sorghum yields in 2022 are still higher than those in 2021. This is due to the irregularity of the rains observed in 2021. Indeed, sorghum yields are considerably influenced by water availability in quantity and time (Ouedraogo *et al.*, 2020; Guébré, 2021). The improved water and chemical properties are the result of organic fertilizer inputs and the breaking of the surface crust, which allowed for better water penetration (Zongo, 2017; Kimaru-Muchai *et al.*, 2021). Also, *zaï* favors the increase of carbon and nitrogen content of the soil. Thus, the addition of micro-dose fertilizers associated with good water retention capacity has boosted sorghum yields.

Conclusion

The results of our study showed that *zaï* pits and *zaï* pits associated with stone rows improved soil pH value, carbon, nitrogen and phosphorus contents. The addition of nitrogen (from urea and NPK), potassium (from NPK), phosphorus (from NPK) and manure to the *zaï* pits and stone rows increased the availability of nutrients in the soils, thus stimulating sorghum vegetative development and yields. Based on our results, the addition of manure and mineral fertilizers in microdose form to *zaï* pits and *zaï* pits combined with stone rows are more competitive climate-smart combinations for improved sorghum production and soil management.

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Collecting of Baobab (Adansonia digitata L.) Germplasm for Conservation

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Abstract

Baobab (*Adansonia digitata L.*) domestication and conservation have become necessary due to its increasing global usage and decreasing population. Although the plant is very resilient and survives harsh environmental conditions, its destruction due to anthropogenic and natural forces could lead to its genetic erosion. Therefore, it is important to domesticate the baobab and provide it with the necessary husbandry practices to ensure its survival and sustainable utilization. The objective of the current study was to collect baobab germplasm across the Volta Region of Ghana for conservation. A reconnaissance survey was therefore conducted and followed up with germplasm collecting trips. As a result, 109 accessions of baobab were collected within latitude 5°47'46.24190 N to 7°9'34.15030 N and longitude 0°11'35.25 E to 1°8'36.74180 E. The collection were made from mangrove swamps, woodland savannah, grassland savannah and deciduous forest across the 18 districts / municipalities of the Volta Region. The collected baobab accessions (scions) were grafted on pre-raised rootstocks. The number of accessions collected were represented on a bar chart and a 3D map was drawn indicating the geographic locations at which the collections were made. The lowest and highest altitudes at the ground at which the accessions were taken were 4 m and 287 m above sea level respectively. The grafted baobab accessions were transplanted at the Ho Technical University ex situ genebank. The collection would help in the maintenance of baobab genetic diversity, serve as materials for studies on baobab and its improvement, and help improve biodiversity.

Keywords: Biodiversity, Deciduous Forest, Ex Situ Genebank, Genetic Diversity, Genetic Erosion

Introduction

Plant genetic resources protect the environment, promote biodiversity and serve as food. However, natural and anthropogenic factors are threats to the survival of plants. These factors are causing the dwindling of the population of many plant species and leading to the risk of their extinction (Quazi *et al.*, 2021). Protection of plant genetic diversity can only be achieved through conscious effort of conservation. Several species are under conservation in different forms all over the world. Despite the conservation actions, some plant species are still not commensurately represented at the genebanks. A typical example is baobab (*Adansonia digitata L.*) which has not received enough conservation efforts.

Baobab is native to Africa and abundant in the arid and semi-arid environments due to its resilience (Assogba *et al.*, 2022). Notwithstanding, it is adapted to a very wide environmental condition (Egbadzor *et al.*, 2023). The wide geographic presence of baobab also reflects its varied uses. These multiple uses include nutritional, medicinal, economical as well as environmental and are well known and documented (Gebauer *et al.*, 2016; Asogwa *et al.*, 2021). Leaves, root tubers, fruits and flowers of baobab are food for many people in Africa (Bamalli *et al.*, 2014). Baobab leaves for instance are important vegetable in the Sahelian regions (Rashford, 2018). Despite the importance of baobab, it remains undomesticated, underutilized and has received little conservation attention.

The anthropogenic factors that could lead to erosion of baobab genetic resources are numerous and compounded by overexploitation of the plant. As food, the leaves are constantly harvested and the trees do not have leaves on them during the dry seasons in the Sahelian regions of Africa (Berkelaar, 2009; SCUC, 2006). The fruits used to drop to the ground before picked up in the past. However, because of the increasing demand, currently people use different means to harvest the fruits on the tree. Another evidence is the exportation of the fruit and its products to Europe as super food (Buchmann *et al.*, 2010). In some places, due to the increasing demand for land for construction and other purposes, baobab trees are cut down or destroyed.

It has been observed that, there are more mature baobab trees than juveniles in Tanzania (Msalilwa *et al.*, 2020). This could be true for other regions and be a signal for possible genetic erosion for baobab in the future if conscious efforts are not made to change the scenario. This has led to the call for conservation strategy to sustain baobab genetic resources (Assogba *et al.*, 2022; Abere *et al.*, 2023). Similar call was made for other minor and underutilized tree crop species in the tropics (Finetto, 2001). Dependence on the wild baobab is not sustainable, hence, domestication and conservation of the plant is essential to forestall its genetic erosion.

The Ho Technical University (HTU) embarked on baobab research and domestication in 2019 to address the neglect of the species (Egbadzor *et al.*, 2022). One of the studies at the HTU revealed that genetic diversity exists within the baobab germplasm in the Volta Region (Egbadzor, 2020). This is in tandem with the within and between baobab provenances differences in West Africa reported by Kalinganire *et al.* (2023). In order to domesticate, selection is made from the available diverse germplasm. Conserved germplasm serves as bank from which selection can be made for domestication. Collection has been identified as an important activity and precedes conservation (Migicovsky **et al.**, 2019). The objective of this study therefore, was to collect the baobab genetic resources from the Volta Region of Ghana for conservation and further studies. The collecting exercise would serve multiple purposes including promotion of biodiversity, germplasm for baobab impovement, climate change mitigation and genetic studies (Adekunle & Jiangang, 2022).

Materials and Methods

The collecting area

The baobab germplasm was collected from across the Volta Region of Ghana. The southern part of the region is mostly flat land with low altitude; some areas are only few metres above sea level. The northern belt of the region on the other hand is mainly mountainous, with Mount Afadza (885 m above sea level) being the highest peak in Ghana. The region has tropical climate, characterized by moderate temperature, 21 - 32°C for most of the years (Nyatuame *et al.*, 2014). The annual rainfall in the Volta Region increases from the south to the north. It is less than 1000 mm on the coast in the south and between 1000 and 1400 mm in the middle belt. In the northern part of the region, the annual rainfall is between 1400 and 1900 mm (Logah *et al.*, 2013).

The vegetation types of the Volta Region are savannah, semideciduous forest and mangrove (Abubakari *et al.*, 2012; Tufuor, 2012). The mangrove is found on the coast in the south while the savannahs (savannah grassland and woodland savannah) and the deciduous forest form a mosaic at the other parts of the region with the forest mainly on the high grounds and along rivers. The soil types in the region include; Chromic Vertisols, Dystrict Nitosols, Ferric Acrisols, Ferric Luvisols, Gleyic Luvisols and Lithosols (Mul *et al.*, 2015).

Volta Region shares borders with the Eastern and Greater Accra Regions in the west and Oti Region in the north. In the south, it is bordered with the Gulf of Guinea and in the east by the Republic of Togo.

Reconnaissance survey

A reconnaissance survey was made to the various districts in the Volta Region prior to the main collecting expedition. This trip was used to establish relationship between the data collecting team and the community members who subsequently assisted in collecting the baobab germplasm.

Germplasm Collecting

Germplasm was collected from the 18 administrative districts and municipalities of the Volta Region. Both random and biase samplings (Dinkar *et al.*, 2023) were made and data collected based on collecting descriptors of Kehlenbeck *et al*. (2015). Baobab trees were selected from clusters in most cases, only few accessions were taken from solitary plants. In the case of solitary plants, they were picked from places where they were perceived to be endangered for instance the possibility of being destroyed for the use of the land for construction. In clusters, the oldest looking tree but healthy was selected. The next tree was at least 300 metres away, in most cases, from a different community. Morphological distinctiveness was also considered. Although, plants were chosen at random, some were not included because of difficulty in accessing them, for instance, some of the trees were too tall for scion collection. Unique environments were also considered such as close to lagoon, on mountains and rocky lands.

Scions were taken from selected baobab trees. In some cases, the collectors used ladder to climb the baobab trees and harvested scions with sickle knife mounted on a long pole. Samples of collected scions are shown in Fig. 1.

Fig. 1: Some collected scions ready for grafting

The nursery

Nursery was establihed at the HTU prior to scion collection (Fig. 2). Pre-germinated baobab seeds were planted in topsoil filled 30 x 20 cm nursery bags and nurtured four months before scion were collected. Seeds for rootstock were taken from the accession AD004. Seeds from this accession has been used as rootstock at HTU since 2019 and has been found to be fast growing (Egbadzor *et al.*, 2023). It was also assumed that seeds from AD004 would produce rootstock that is adapted to the conservation site as its place of collection is not far. Differences in seedling performance could however, occur because pollen might have come from a distant tree to pollinate AD004. The collected scions were grafted a day after collecting them. The point of grafting on a rootstock varied from 25 to 30 cm above the soil level and the thickness of the stems were about one cm thick. The average size of scions was therefore about one cm thick. At least five samples were grafted from each accession with the aim of transplanting three of them to the field.

Fig. 2: Technicians working at the baobab nursery

Field Conservation

Bushes were cleared and shrubs and trees chopped followed by stumping and ploughing. Lining and pegging was done and planting holes dugged and manured in preparation for planting. All the accessions were planted on 30th of April, 2024, about two months after grafting at HTU ex situ genebank.

Data analysis

The number of baobab accesssions collected per district / municipality was represented on a bar chart drawn using GenStat edition 12 (Payne *et al.*, 2009) and a 3D map drawn showing the geographic points of collections with Excel.

Results and Discussion

A total of 109 baobab accessions were collected from the eighteen administrative districts and municipalities of the Volta Region of Ghana (Fig. 3). The number of accessions collected from a district or municipality ranged from one at Anloga District to 11 from Adaklu District. The factors which determined the number of accessions collected included the abundance of the species in the area, the size of the district, convenience in sampling and visible variability in the plants. Anloga Distict which is located on the coast is relatively small (322 km^2) and has only few baobab plants. Adaklu Distict on the other hand has a large land area (800 km^2) and it is smaller than only North Tongu (1,154 km^2) and Ho West (992 km^2) in the Volta Region. In addition, Adaklu District was easily accessible to the research team, and also has a lot of baobab trees which justified the collection of more accessions.

Ten accessions each were collected from the Ho Municipality and South Tongu District. Relatively high collections of seven to nine were also made from Agortime-Ziope, Central Tongu and Ketu North Districts and Keta Municipality. There is high population of baobab in these districts and municipalities also, which warranted the collection of more accessions. Between three and six collections were made from the rest of the districts. This baobab collection could be the highest number of baobab germplasm under ex situ field conservation by a single institution currently. Documentation on baobab (*A. digitata*) conservation is scarce. This could be explained by its orphan state. Also, few records on its conservation are in form of seed conservation at genebanks and not as ex situ field conservation. In the case of field conservation, the baobabs are mainly in situ and not ex situ (Assogbadjo *et al* 2010). Although ICRAF holds 394 accessions as the largest collection of baobabs, most of them are conserved as seeds and not yet in field genebanks. The second largest reported baobab collection are 128 accessions kept at the global seed vault at Svalbard (Global Seed Vault, 2024). The United States National Germplasm System has 11 baobab accessions in its seed genebank (USDA, 2024). The Millennium Seed Bank, Kew also has 2 baobab accessions (Kew 2024).

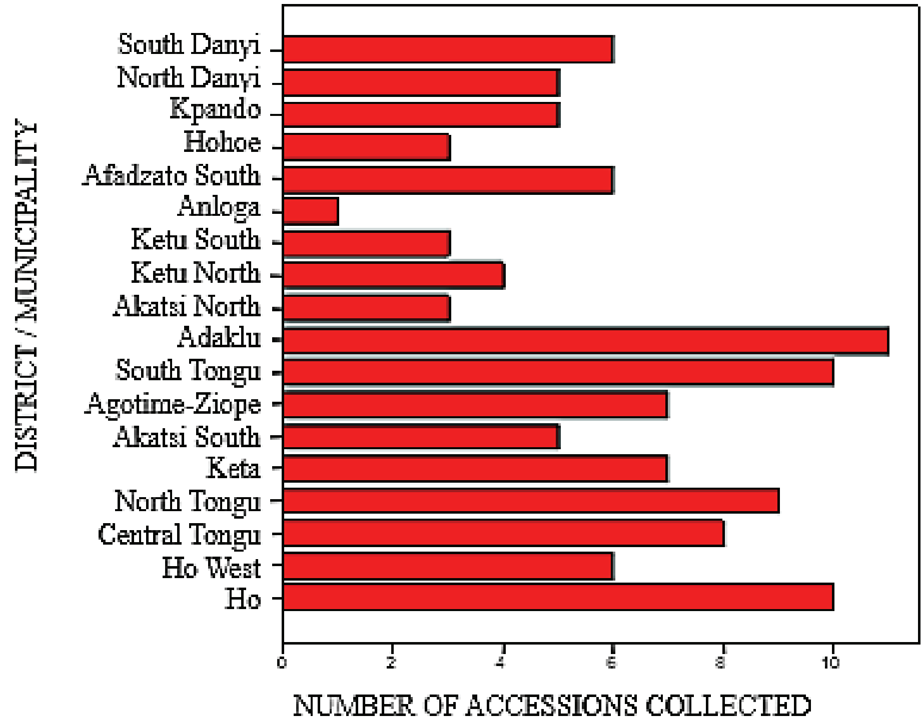

Fig.3: Number of baobab accessions collected from each district or municipality

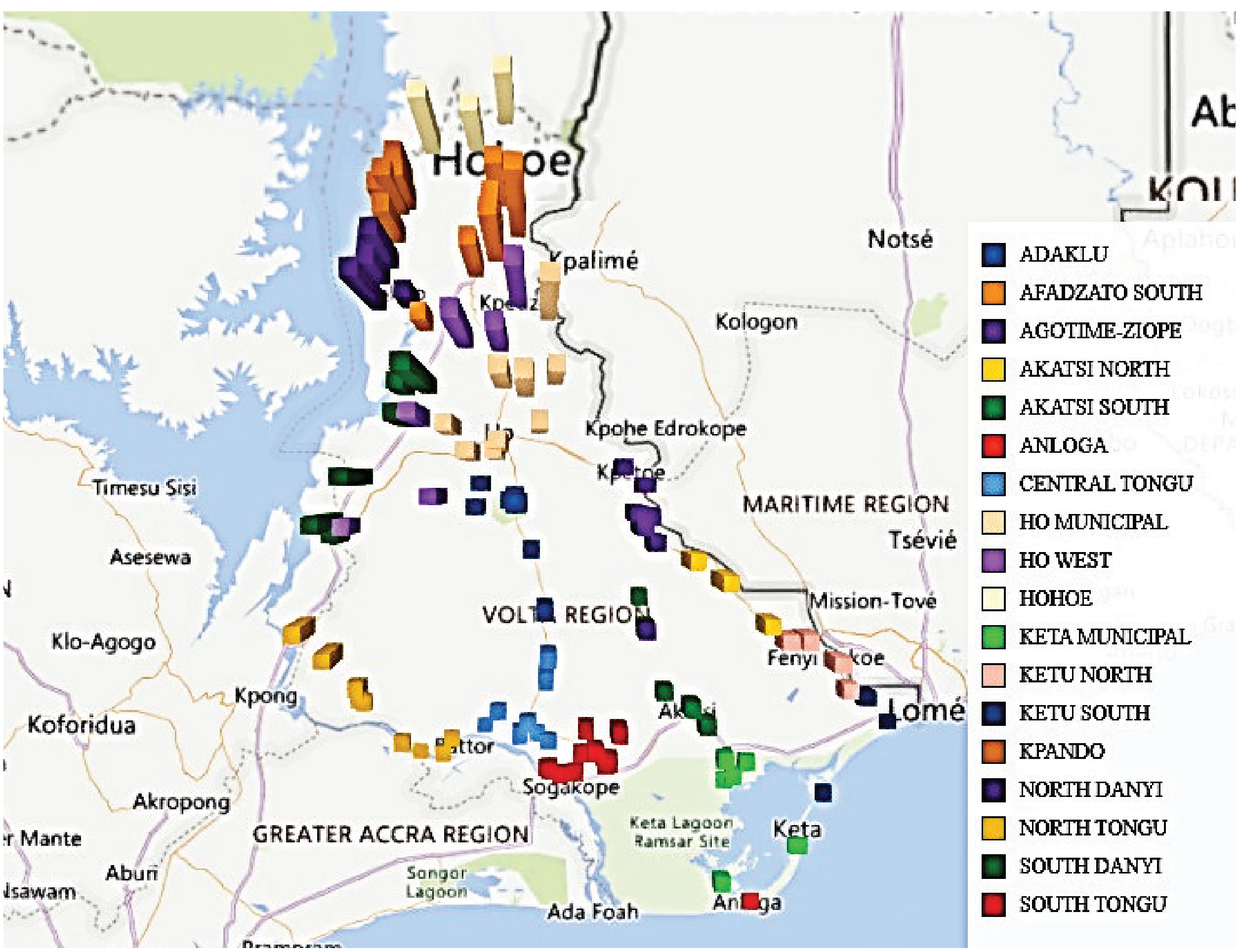

Fig. 4: Map showing geographic locations of the collected baobab accessions

The geographic locations at which the collections were made are represented in Fig. 4. Points with similar colours show baobab accessions that were collected from the same administrative district or municipality. The height of a point is related to the altitude at the ground of the tree from which the scion was taken from. Geographically, the baobab accessions were collected within latitude 5°47’46.24190 N to 7°9’34.15030 N and longitude 0°11’35.25 E - 1°8’36.74180 E. The corresponding communities of these geographical points are Sanga in the South Danyi District, Agbenorxevi in the Ketu South Municipality, Anloga Agorue in the Anloga District and Hohoe Zongo in the Hohoe Municipality. Thus the most westward and eastward collecting points of the baobab accessions were Sanga and Agbenorxevi respectively, while the most southward and northward were Anloga Agorue and Hohoe Zongo respectively. In terms of altitude, the accessions were colleccted from 4 m above sea level at Agbenorxevi, a community in the Ketu South Municipality to 287 m above sea level at Keklebi Duga in the Afadzato South District and Goviefe Todzi in the South Danyi District. The Volta Region is characterised by both low and high altitudes. The low altitude areas are from the coast to Agotime-Ziope District. Higher grounds are found around Adaklu and Kabakaba Mountains in Adaklu District and Ho Municipal respectively (Tufuor, 2012). Also, the Awkapim-Togoland range at Afadzato South, Ho West, South and North Danyi Districts and Hohoe and Kpado Municipalities make these areas high grounds. In addition, the corresponding valleys also create low altitudes at some places in the mountainous areas.

The distribution of baobab throughout the Volta Region is an indication of its wide adaptability (Egbadzor *et al*., 2023b). Future climate variability may not have much detrimental effect on the plant, however, competition for land for other developmental projects may pose a big threat. The suggestion of Assogba *et al*. (2022) for the conservation of the baobab is therefore in the right direction. Evidence of anthropogenic factors including over harvesting of bark and destruction by chopping or torching of baobab trees were observed during the collection mission. People are destroying baobab trees to use the land for building purposes.

The baobab plants were seen either standing alone in isolation or in clusters similar to the report of Gebauer et al. (2016) and Musyoki *et al*. (2022). Cluster sizes varied from place to place interms of density and area covered.

Conclusion

The baobab germplasm collection exercise in the Volta Region of Ghana was successful and resulted in the collection of 109 accessions. These accessions will be conserved ex situ at HTU farms and serve as materials for further studies. Collection was not possible at some places because of difficulty in accessing the trees. Some other trees were too tall for scions to be harvested. However, the collected accessions were expected to have a lot of diversity which is worth further studies to establish how much of the species diversity is being conserved.

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Conflict of interest

The author does not have any conflict of interest to declare.

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Enhancing Sustainable Bambara Nut (*Vigna Subterranea* (L.) Verdc) Production In Busia County, Western Kenya: A Survey Of Farmers' Knowledge on Cultivation and Production.

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Abstract

A study was conducted in the Butula sub-county of Busia County to determine farmers' knowledge of the cultivation and production constraints of Bambara nuts. The survey involved the administration of questionnaire-based interviews to Bambara nut farmers. A total of 40 farmers were purposively sampled for the study. Information was collected on various aspects, and the data was analyzed using SPSS software version 23 by the use of descriptive statistics based mainly on percentages. From the analysis, it was observed that the crop is mainly grown by women (87.5%). Most of the area under Bambara nut cultivation was less than 1/8 of an acre (70%). Bambara nut was basically grown for food (57.5%) and as a sole crop with black and red landraces being the most dominant ones. The crop was planted during the short rain seasons, with very low yields being reported, where only 4% of the people had yields of more than 50 kg in relation to the area planted. The low yields were attributed to a lack of improved varieties, a lack of knowledge of pests and disease management, and poor agronomic practices. The crop was also noted to perform poorly in the presence of heavy rains. Most farmers (65%) were aware of pests and diseases but 92.5% of them did not manage them. The study indicated a lot of growth potential for Bambara nut in Busia County and its contribution to promoting the nutrition, living, and health status of smallholder farmers in the region.

Key words: Bambara nut, cultivation, production constraints, crop management.

Introduction

Bambara nut (*Vigna subterranea* (L.) Verdc) is a legume of great importance in most parts of sub Saharan Africa, Kenya being inclusive. The crop ranks third in production after ground nuts (*Arachis hypogaea L.*) and cowpeas (*Vigna unguiculata L.*) [1]. Bambara nut is highly nutritious (contains 49-63.5% carbohydrates, 15-25% protein, 4.5-7.4 lipids and 5.2-6.4% fiber) and has been used as a major component in various food products improving human nutrition and health [2]. The crop also improves soil fertility by fixing atmospheric nitrogen with the aid of *Bradyrhizobium* bacteria giving acceptable yields on soils that other crops usually fail [3]. This makes Bambara nut an important crop in resolving malnutrition, poverty and food security problems in rural setups of Kenya. In addition, the crop has several medicinal values. For example, the leaf sap is used to treat infected wounds and epilepsy, roots act as aphrodisiac while pounded seeds treat eye cataract. Landraces containing relatively high levels of soluble fibers are thought to reduce incidences of heart disease, colon cancer and diarrhea [4]. In Kenya, Bambara nut is mainly grown at the Coast, Eastern, Western and Nyanza regions [5].

As one of the indigenous crops Bambara nut production has remained low with its potential value being underexploited placing it in danger of genetic erosion and disappearance that further restricts its development options [6]. There is therefore the need to intensify scientific studies aimed at improving Bambara nut production and germplasm conservation. In comparison with other legumes such as beans and cowpeas Bambara nut has a higher market value [7]. The crop is mainly grown by small holder farmers for subsistence purposes with very few growing it for commercial reasons. Continuous dependence by farmers on indigenous crop production techniques that are of old age experience without adapting current production technology has contributed to the low yields of the crop [8]. For farmers to reap great benefits from the crop improved agronomic practices have to be incorporated in the production [9].

Recent studies indicate an increase in commercial production and marketing of Bambara nuts in Africa as a whole with more institutions and stake holders working collaboratively to see to it that the crop's production is increased [10]. In as much as increase in Bambara nut production is more promising very little research has been done regarding its production potential on a commercial basis or exploitation of some of its germ plasm for higher yields and some nutritional characteristics. A lot of pest and disease negligence has also been reported among Bambara nut farmers with an assumption that the nut is disease tolerant [11] [12].

This has led to continuous increase in the biotic stresses and the situation has been made worse by the poor production practices and poor post-harvest handling techniques.

Lack of such technical information is one of the key factors hindering Bambara nut production. The available landraces in Kenya have resulted from self-selection by farmers from previous harvests with no improved varieties being developed and this is a similar case in most Bambara nut growing areas [13]. There is also very little understanding by farmers on the optimal cropping practices and farm management techniques needed for increased production of the crop. Most of the research and development options should be built on some of the traditional practices that are of sound scientific principles [14]. There are limited studies on Bambara nut cultivation and best pest management practices. Therefore, this survey was carried out with an aim of identifying and documenting farmers' knowledge on the cultivation and production constraints of Bambara nut so as to enhance the crop's sustainable production.

Study Methodology

The study was carried out in the short rain season of between September and December 2015 where most farmers grow the crop. The study area (Butula sub-county) in Busia county of Western Kenya was selected based on consultations with the agricultural and extension officers in the county who identified the sub-county as the most pre dominant Bambara nut producing region. Purposive sampling was used where only Bambara nut farmers were selected for the interview. Within the sub county a total of 40 Bambara nut farmers were interviewed. A structured pre-tested questionnaire was administered to the farmers and the data analyzed using SPSS software. Differences among various parameters were determined using descriptive statistical values mainly percentages using SPSS software version 23.

Results

Gender and age: Most of the Bambara nut farmers were women (87.5%) with very few men engaging in the crop's production (12.5%). Majority of these farmers were aged between 20-40 years and 61 years and above (40% each) with only 20% of the farmers being of ages between 40-60 years (Table 1).

Production practices: Most farmers in Butula sub county own more than 1 acre of land (60%) but very little land has been set aside for Bambara nut production where most of the farmers (70%) have less than or equal to 1/8 acre for production of the crop. All the farmers indicated that they grow the crop during short rain periods i.e. between the months of September and December every year. Bambara nut seems to be an indigenous crop for this region since a huge percentage (77.5%) of the farmers has grown the crop for more than 3 years. Despite having been grown for many years the crop's yields are still very low with most farmers (47.5%) harvesting between 1-25kg and only 4% recording a yield of more than 50kgs (Table 2).

Table 1: Socio-demographic information

		Frequency	Percent	Cumulative Percent
Gender of respondent	Male	5	12.5	12.5
	Female	35	87.5	100.0
	Total	40	100.0	
Age	20-40 Years	16	40.0	40.0
	41-60 Years	8	20.0	60.0
	61 Years and above	16	40.0	100.0
	Total	40	100.0	
Village	Madola	10	25.0	25.0
	Butunyi	14	35.0	60.0
	Bufisi	6	15.0	75.0
	Bukati	10	25.0	100.0
	Total	40	100.0	

Bambara nut farmers in Butula Sub County mainly grow Bambara nut for consumption (57.5%) with very few (2.5%) of them growing it as a cash crop. However, 40% of the farmers grow the crop for both food and commercial purposes. In most farms (42.5%) the crop is grown near to the homestead with others (32.5%) growing it furthest from the homestead. When it comes to landraces grown the most commonly available landraces are the black and red landraces (35%). The other landraces are represented in small percentages but at-lease there is a diverse group of landraces. Bambara nut in Butula Sub County is mostly grown as a sole crop (52.5%) with 45% of the farmers intercropping with other crops (Table 3). After harvesting the crop farmers often store their produce in unshelled form (92.5%) with only 7.5% of them shelling before storage (Table 4).

Table 2: Land use information

		Frequency	Percent	Cumulative Percent
Farm size (acres)	≤1/4	3	7.5	7.5
	1/2	4	10.0	17.5
	1	9	22.5	40.0
	> 1	24	60.0	100.0
	Total	40	100.0	
Area (acres) under bambara nut production	≤1/8	28	70.0	70.0
	1/4	5	12.5	82.5
	1/2	6	15.0	97.5
	>1	1	2.5	100.0
	Total	40	100.0	
Growing season	Short rain season	40	100.0	100.0
Years of cultivation	1-2 Years	9	22.5	22.5
	≥3 Years	31	77.5	100.0
	Total	40	100.0	
Yield (in Kgs) realized previous year (shelled or unshelled)	1-25	19	47.5	47.5
	26-50	17	42.5	90.0
	>50	4	10.0	100.0
	Total	40	100.0	

Production constraints: Farmers were able to identify various problems contributing to the low yields of the crop with majority (37.5%) of them stating lack of improved varieties and others close to 25% attributing the low yields to poor soil fertility.

Other problems cited included pest negligence where farmers were not aware of the damage caused by pests and diseases, lack of knowledge on improved production techniques where most farmers were still relying on the traditional farming methods. Farmers also indicated the negative impact of heavy rain falls on the crop's yields which caused a lot of pod- rotting (Table 3).

Table 3: Crop production

		Frequency	Percent	Cumulative Percent
Reasons for growing bambara nut	Food	23	57.5	57.5
	cash crop	1	2.5	60.0
	Food and cash crop	16	40.0	100.0
	Total	40	100.0	
Part of the farm in which bambara is grown	Nearest the house	17	42.5	42.5
	Mid	10	25.0	67.5
	Furthest from the house	13	32.5	100.0
	Total	40	100.0	
Landraces grown	Black	14	35.0	35.0
	Brown	4	10.0	45.0
	maroon speckled	1	2.5	47.5
	Brown speckled	1	2.5	50.0
	Black and Red	14	35.0	85.0
	Black and Brown	6	15.0	100.0
	Total	40	100.0	
Cropping system	Intercropped	18	45.0	45.0
	Sole	21	52.5	97.5
	Rotation	1	2.5	100.0
	Total	40	100.0	

Most farmers (65%) were aware of pest problems in their Bambara nut fields. Some of the pests reported included aphids, bollworms and weevils. Farmers were able to report disease symptoms where wilting (25%) of the crop was the most recorded symptom. Other symptoms reported were leaf chlorosis and necrosis, Cercospora leaf spots, seed damage and brown discoloration of vascular bundles. Despite being aware of pests and diseases 92.5% of farmers did not practice any pest management practices (Table 4).

Table 4: Crop management

		Frequency	Percent	Cumulative Percent
Storage	Shelled	3	7.5	7.5
	Unshelled	37	92.5	100.0
	Total	40	100.0	
Major problems contributing to low Bambara nut yields	Heavy rains	2	5.0	5.0
	Lack of production knowledge	6	15.0	20.0
	Pest negligence	3	7.5	27.5
	low soil fertility	10	25.0	52.5
	Lack of improved varieties	15	37.5	90.0
	Labour intensive	4	10.0	100.0
	Total	40	100.0	
Awareness of Bambara nut pests	Yes	26	65.0	65.0
	No	14	35.0	100.0
	Total	40	100.0	
Pests	Aphids	5	12.5	12.5
	Bollworms	14	35.0	47.5
	Weevils	7	17.5	65.0
	N/A	14	35.0	100.0
	Total	40	100.0	
Symptoms	Wilting	10	25.0	25.0
	Leaf chlorosis	4	10.0	35.0
	Leaf necrosis	2	5.0	40.0
	Discoloration of vascular bundles	1	2.5	42.5
	Leaf spots	2	5.0	47.5
	Seed damage	7	17.5	65.0
	N/A	14	35.0	100.0
	Total	40	100.0	
Diseases/pest Management	Uprooting diseased plant	1	2.5	2.5
	Crop rotation	1	2.5	5.0
	None	37	92.5	97.5
	Uprooting diseased plant and crop rotation	1	2.5	100.0
	Total	40	100.0	

Discussions

Gender and age: Most women were reported to practice Bambara nut production in comparison to men in Butula sub county since the nut is still branded a women's crop in this region. In other countries a higher number of women growing Bambara nut in comparison to men has also been reported [7, 8, 9]. Such figures impact negatively on gender considerations when it comes to adaptation of current technologies aimed at improving Bambara nut production in Kenya. More youths and the elderly people were reported to grow Bambara nuts in the region. This is similar to the study carried out in Southern Guinea savanna of Nigeria [].

Acreage and crop yields: Very small areas of land are set aside for Bambara nut production in Butula sub county with very low yields attained. Most of the land is set aside for production of main stream crops such as common beans and maize. This trend again places Bambara nut in danger of genetic erosion and disappearance. There were no accurate yield figures reported other than estimates and this is attributed to the fact that the crop is consumed much at the immature stage while in the fields. This coincides with the study carried out in southern guinea savanna of Nigeria [15]. The low yields are related to lack of improved varieties since farmers grow the crop from their own saved seed or the local landraces available in the markets. Poor soils and lack of improved agronomic practices also contributed to low yields in the crop. The same reasons were reported by famers in the upper east regions of Ghana [9] The yields of the crop also varied greatly with the type of landrace planted. Farmers also indicated that Bambara nut production is labor intensive compared to other legumes and this has contributed to many people shunning its production.

Time of planting: All the farmers indicated that they grow the crop during the second growing season (September –December) after the harvest of the major crops (maize and beans) has been completed. This is a short rain period where the crop does well since it is normally damaged by heavy rains. The same season has been adapted in the guinea savannah zones of Ghana [ ] and Upper west regions of Ghana [. However in the year 2015 the crop yields were generally low due to the heavy short rains (787 mm) compared to the year 2014 (655 mm) (http://me.awhere.com). These conditions may have enhanced fungal disease sporulation and hence the poor performance.

Pests and diseases: Farmers reported different pests as being problematic to Bambara nut production. Weevils were reported to attack the crop during storage due to poor post-harvest handling of the crop. Most farmers do not dress their produce with any insecticide. They also lack proper storage facilities. This problem of weevils' attack due to poor post handling techniques had also been observed in in Nigeria [16]. Aphids and bollworms were reported to be present in the fields. A study carried out in north eastern Nigeria on bambara nut production also indicated pests and diseases as some of the factors contributing to low yields in the crop [.

The most widespread disease symptoms reported by farmers included wilting, leaf spots and chlorosis and seed damage by bollworms. These symptoms are an indication of some of the diseases reported to attack the crop such as Fusarium wilt, Cercospora leaf spots and leaf blotch [3] that need further interventions.

In as much as farmers were able to report pest and disease attacks many did not have any knowledge on their management and simply neglected these problems with an assumption that the crop is pest tolerant. Only 2.5% of the farmers uprooted the diseased plants and practiced crop rotation. None of them used pesticides. The same findings were reported by other researchers [7] [ ]. Such findings are an indication of disease epidemics on Bambara crop if there are no intervention measures in place.

Cropping systems: Unlike in other parts of Africa such as Nigeria where most farmers practiced intercropping [15] in Butula sub county many grow the crop as a sole but on small areas where they indicated that this type of cropping aids in the reduction of pest and disease populations. This is in agreement with the fact that intercropping may create room for alternate pest hosts leading to increase in diseases. However, a good number of farmers also practiced intercropping system especially with cassava as seen in figure 1. For the farmers that practiced intercropping much of the intercrop was with cassava and maize and their main reason was for economical land use. Other scientists have also reported that many farmers often practice intercropping due to factors such as efficient use of land resource and population pressure [ ] [ ].

Figure1: Bambara nut intercropped with cassava

Conclusion

Bambara nut is an indigenous crop that has been grown for many years by subsistence farmers in Busia County. The crop yields however still remain low due to various factors such as dependence on traditional methods of cultivation.

Farmers also still grow the crop on small pieces of land with much of the area being used for other cash crops since very few farmers grow it for commercial purposes. Farmers do not use fertilizer in Bambara nut production and in as much as they reported pest and disease attacks many of them lack the knowledge on the management practices. No pesticides are applied to control the pests. Most of the efforts to produce the crop have been left to the women (Figure 2) and its production is not a whole family concern. The kind of seed used is locally accessed with no improved varieties. These local landraces are low yielding and susceptible to diseases. Post-harvest handling of the crop is also poor leading to pest attacks.

Figure 2: Hand weeding of Bambara nut crop in the field by an elderly woman

Farmers do not dress their seeds with any insecticides before storage, however a few of then use ash as a preservative method. They also do not store their produce in the right facilities making them vulnerable to pest attack such as weevils. This often leads to loss of seed vigor and marketability. This calls for the need of farmers to work closely with crop specialists such as agronomists, entomologists and plant pathologists in various field inspections for pest, diseases and crop performance. This study indicates a lot of Bambara nut negligence by the political and scientific community. Very little efforts are being made to improve Bambara nut production in terms of producing certified seeds, breeding for pest and disease resistance and high yielding varieties.

Recommendations

There is need to develop improved varieties that are high yielding and resistant to pests and diseases.

There is need to produce quality and certified Bambara nut seeds for increased crop yields.

Farmers should be educated on the importance of Bambara nut production so as to increase the production acreage.

The government should create market for the produce since the crop has a higher market price per unit kg in comparison to other legumes. This will encourage farmers to produce the crop in large quantities.

Farmers should be educated on the current agronomic practices such as pest and disease management techniques that lead to higher crop yields.

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Parallel Session 2

The Role of Digitalization, Artificial Intelligence, and Precision Agriculture in Climate Mitigation and Adaptation

Optimising Farm Decision-Making for Climate Resilience: A Review of Digital Technologies in Eastern Africa

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Abstract

Climate change poses a significant threat to agricultural productivity in Eastern Africa. Digital technologies offer promising solutions to enhance climate resilience and improve decision-making among farmers. However, limited awareness and access to these tools hinder their widespread adoption.

This review explores the potential of various digital agricultural technologies to support climate-smart agriculture (CSA) practices in Eastern Africa. Specifically, the review addresses the following questions: (i) What digital tools have successfully been used by farmers on a relatively large scale? (ii) what opportunities do digital innovations bring to CSA? (iii) how can digital innovations increase the adoption of CSA technologies and innovations in Uganda, Kenya and Rwanda?

The authors leveraged their experience from implementing research-for-development projects focused on digital extension services, disease diagnostics, and green technologies to identify thirteen key digital tools currently utilised by community extension agents and lead farmers in Uganda, Kenya, and Rwanda. These tools serve a range of functions including (i) dissemination of information about seasonal weather forecasts, pest and disease alerts and identification (ii) Risk mitigation through the provision of weather-based index agricultural insurance services, (iii) increased efficiency in the use of productive resources such as irrigation water and fertilisers, (iv) improved access to markets through the provision of market information and linkage to off-takers, (iv) Promotion of eco-friendly and sustainable farming practices including green technologies and sharing of farm mechanisation tools (v) increased access to agricultural e-financial services in rural areas and several specific needs of farmers.

The review further highlights the broader benefits of these technologies beyond climate resilience. They can improve farmer literacy, adherence to production protocols, information-seeking behaviour, negotiation skills, and ultimately, household income. Notably, these tools empower women and youth by providing educational opportunities that transcend time and location constraints.

Keywords: Climate Smart Agriculture, e-extension, Information and Communications Technology (ICT), multistakeholder partnerships, farmers, e-Agriculture

Introduction

The agricultural sector is the economic cornerstone for all East African countries where agriculture employs 41.9%, 61%, and 47% of the total population in Kenya, Uganda, and Rwanda respectively [UBOS 2024a; NISR 2024a; KNBS 2024]. Agriculture also contributes 21.8%, 24.6%, and 27% to the GDP of Kenya, Uganda, and Rwanda respectively [UBOS 2024; NISR 2024b; KNBS 2024]. The agriculture sector remains relevant to the food and nutrition security of these countries.

The deliberate effort by most East African Governments to transform and modernise agriculture in the recent past has contributed to the emergence and significant proliferation of agriculture-supported Information Communication Technology (ICT) tools – ranging from text message and interactive voice response (IVR) systems to mobile apps, satellite imaging, and remote sensing [NPA 2017; MoALF 2019; MINAGRI 2018]. This has also been facilitated by the increased access and availability of digital infrastructure in the three countries. For example, 99% of Rwanda is covered by 3G fibreoptic cable and 4G LTE networks while 5G network coverage is on the rise. Internet penetration or access is growing and ranges from 25 - 40.8% in Kenya, 14 – 27% in Uganda and 9 – 34.4% in Rwanda [Osiemo *et al.* 2021; Social & Meltwater 2024]. Over 98%, 50% and 49% of the population own mobile phone in Kenya, Uganda and Rwanda, respectively [Osiemo *et al.* 2021; Kropff *et al.* 2020; Gillwald *et al.* 2019; Social & Meltwater 2024].

Digital technologies overcome information problems hindering market access for many small-scale farmers, increase knowledge through new ways of providing extension services, and provide novel ways to improve agricultural supply chain management [Deichmann *et al.* 2016]. Digital technologies also improve efficiency by decreasing financial and labour costs, providing information to support management decisions, increasing product quantity and/or quality, reducing losses, and/or ensuring effective and sustainable use of resources [Abate *et al.* 2023]. Digital technologies have also been used to solve challenges associated with product quality, monitoring, traceability, pricing, cold-chain and storage, value-addition, automation, and communication, especially among agro-input dealers, distributors, and consumers [Abate *et al.* 2023]. The use of mobile phones was also reported to reduce the cost and increase access to agricultural extension services and advisory services in Rwanda [Stokke 2019]. This complements the in-person provision of agro-advisory services to farmers which is usually through government agriculture officers and private community-based extension agents who in most times are overwhelmed by the huge number of farmers they serve. The use of ICT to support extension and advisory services become more relevant in these countries especially where the extension-to-farmer ratio is so low standing at about 1:1,800 for Uganda, 1:1078 for Kenya and 1:136 Rwanda [MAAIF 2019; Chibi 2023; Mabaya *et al.* 2021].

Farmers in East Africa are grappling with increasing climate shocks, more frequent extreme weather events, and accelerated environmental degradation that negatively impact yields hence reducing agricultural productivity [IPCC 2023; MUBENGA-TSHITAKA 2023]. The power of digital technologies and decision-support tools has also been shown as one of the climate-smart approaches to support farmers to adapt to climate change and enable them to sustain and improve agricultural yields [Deichmann *et al.*, 2016; Abate *et al.*, 2023]. The use of digital tools to access climate services has been reported to increase the adoption and utilization of several other climate-smart agricultural technologies and practices hence minimising the negative impacts of climate change on food security and farmer livelihoods [Mulwa *et al.* 2017; Djido *et al* 2021].

Several reports exist on the increased adoption of ICT-based innovations in supporting smallholder farmers to adapt to climate change. For instance, farmers in Rwanda who received climate information through Radio Listening Clubs and Participatory Integrated Climate Services for Agriculture (PICSA) reported a 47% increase in the value of crop produced and a 56% increase in income from crops [Birachi *et al.* 2020]. In Tanzania and Malawi, the use of simple soil moisture and nutrient monitoring digital tools in smallholder irrigation schemes resulted into increased yields, reduced water wastage and reduced conflict over water in irrigation schemes [Stirzaker & Driver, 2024]. The use of digital finance services such as phone-based payment systems to facilitate market transactions and financial services was reported to lower transaction costs and risks, improve efficiency and improve quality assurance and traceability of agricultural products hence contributing to reduced carbon emissions within the entire agriculture supply chain [Lee & Wang 2022; Parlasca *et al.* 2022; Abate *et al* 2024].

Most of the digital innovations in East Africa are built on the architectural designs of mobile phones, interactive voice responses, radio, television, websites and social media platforms.

1. **Mobile phones:** These use either text messaging services (SMS), Mobile phone apps and call centres.
2. **Interactive Voice Response (IVR):** IVR systems allow farmers to call a hotline and listen to pre-recorded messages on a variety of agricultural topics. IVR allows farmers to choose a language of their choice and to listen to the messages at a time of their convenience. IVR also allows farmers to listen to any message more than once.
3. **Radio:** Radio is a traditional communication channel that is still widely used in East Africa. Radio programs can be used to broadcast agricultural information to a large audience and radios also broadcast in several local languages that farmers understand.
4. **Websites and web-based platforms:** These platforms provide farmers with access to a wealth of agricultural information, including articles, videos, and downloadable resources. Some platforms also allow farmers to connect with extension workers and other farmers online. These include blogs, YouTube channels and websites.
5. **Social media:** Social media platforms such as Facebook, WhatsApp, and Twitter are being used by extension services to connect with farmers and share information. Farmers can also use these platforms to connect and share knowledge and experiences. Social media channels can also be used for coaching and mentoring farmers.
6. **Television and video-based approach to agricultural extension:** Recorded videos are aired on TV as reality and education episodes or played to a group of farmers in remote areas. The content is then discussed with the aid of the facilitator. This approach increases smallholder farmers' knowledge of using low-cost climate-smart agriculture innovations. The approach helps to deliver key messages to the farmer in an entertaining way and yet it is educational at the same time [CCAFS, 2015].

Despite the importance of ICT tools to the agricultural sector in these three East African countries, there is inadequate information in the literature on the level of utilisation of digital tools by farmers in East Africa. This limits knowledge and understanding of the most preferred ICT-based tool or the purpose for which the tools are used.

This review presents the available digital platforms in the three countries and gives recommendations of how they can be leveraged on by smallholder farmer to increase productivity and build resilience to climate change in the framework of CSA. Specifically, the review addresses the following questions: (i) What digital tools are currently being used by farmers at a relatively large scale? (ii) how can digital innovations increase the adoption of digital innovations for managing or spreading risk associated with climate change among smallholder farmers? (iii) what opportunities do digital innovations bring to building resilience to climate shocks?

In this paper, agricultural digital innovations are defined as mechanisms that rely primarily on ICT tools to provide information on agronomic advisory services (Good Agriculture Practices (GAP)), weather alerts, insurance, input supply and marketing (including price information, credit provision costs and processing payments). The definition also covers other mechanisms for example digital tools and applications that contribute to reductions in uncertainty, risk, data and increase productivity, data monitoring and analytics, and data-driven solutions in agriculture to improve and/or optimize farming systems, increase crop quality and yield, reduce waste, and manage pest and diseases.

Approach

Since access to much of the academic literature on the current utilisation rates of most agricultural digital platforms or evidence of their impact in East Africa is limited (not in the public domain), partly due to the commercial nature of this business, this paper is neither a systematic review nor a meta-analysis. This paper used a combination of grey literature, case studies, expert knowledge and personal experiences gained by the authors during the implementation of several climate change-related agriculture research and innovation projects in Uganda, Kenya and Rwanda Africa.

The experiences of the authors come from years of implementing projects including (i) Digital Connectors accelerating extension services to farming communities in Kenya and Uganda (ii) Developing a smartphone-based diagnostics platform linking AI image-based disease recognition with microfluidic isothermal amplification diagnostic tools (iii) Unlocking productivity in maize within smallholder farming systems through the use of green and digital farming technologies in the face of climate change and (iv) Information for Agriculture, Food and Water Security. Through the above-mentioned projects, the authors promoted the increased utilisation of agriculture digital innovations such as Plantvillage Nuru, CropDig, and FarmPass through multistakeholder innovation platforms that connect the value chain actors of that commodity. Based on the expert insights and available literature, we compiled an inventory of the digital innovations available in Uganda, Kenya and Rwanda. The digital innovations are listed based on the function they perform.

Unlike previous review papers that highlight the potential use of ICT tools to transform African agriculture, this review focuses mainly on the tools that can support the reduction or spread of risks to crop loss associated with climate change. Our review mainly focuses on the effectiveness of digital tools in facilitating increased utilization of CSA practices and technologies within the three countries. We analyse these innovations within a typology of climate information-related services, covering 13 distinct functions: (a) dissemination of information about seasonal weather forecasts, pest and disease alerts and identification (b) Risk mitigation through the provision of weather-based index agricultural insurance services, (c) increased efficiency in the use of productive resources such as water and fertilisers, (d) improved access to markets through the provision of market information and linkage to off-takers, (e) Promotion of eco-friendly and sustainable farming practices including green technologies and sharing of farm mechanisation tools (f) increased access to agricultural e-financial services in rural areas and several specific needs of farmers, (g) increased access to agronomic and market advisory services (h) collection of agricultural farm and market data (i) increased knowledge through tailored training programs.

Our review covers more recent digital innovations that were being used in the year 2024, keeping pace with the rapidly evolving ICT sector that quickly renders reviews obsolete. Our paper also responds to the gaps in the knowledge of which digital tools are in actual other potential use including providing links to the said digital platforms and guiding on how are being accessed by farmers. Finally, our review limits itself to digital innovations aimed specifically at reducing and spreading risks related to climate change and promoting the increased utilization of climate-smart technologies and innovations.

What Digital Tools Are Currently Being Used By Farmers on A Relatively Large Scale?

This paper presents 15 typologies or categories of how community-based agricultural extension agents and lead farmers are leveraging the available digital tools in 2024 to increase the resilience of agricultural production systems to climate change. The digital tools support decision-making at the farm level to enable farmers to make informed farm management decisions based on weather forecasts, market demand and prices, soil characteristics and pest incidences in the area. Informed decision-making helps to reduce or manage the climate risk associated with climatic change such as drought, floods, pests and disease outbreaks, resulting in low agricultural productivity due to total crop failure or death of livestock. They include:

1. **Community-based agricultural extension/outreach agents:** The case for youth agripreneurs in Uganda and Kenya: This approach used qualified graduates in agriculture who are tech-savvy, rural youth who are involved in some form of agribusiness. The youth agricultural entrepreneurs were trained and mentored for at least 3 months by value chain business experts selected from private sector associations, universities, research institutions or youth organizations at designated facilities called innovation hubs. The youth agripreneurs (referred to herein as "digital connectors") were later supported with a seed capital of ICT equipment such as tablets or smartphones to digitally keep records of their customers, expand their markets and reach more smallholder farmers with either agricultural advisory, agro-inputs or market information. The digital connectors are currently providing services to nearly 13,000 members who belong to four cooperatives i.e. Kangari Dairy Cooperative and Murang'a Avocado Farmers' Cooperative Union, (MAVOC) in Murang'a County, Kenya, Bugiri Agribusiness Institution and Development Association (BAIDA) in Bugiri and Zirobwe Agaliawamu Agri-Business Training Association (ZAABTA) in Luweero district in Uganda. The digital connectors mainly use WhatsApp groups to market their products and services but also buy farm produce from farmers. Some are also using Android apps to communicate with farmers. This has created a platform for efficient communication and transaction between the digital connectors and farmers, facilitated market access and ensured a fairer and more efficient exchange of agricultural products.

2. **Seasonal and Weather forecasting services:** Accessing and disseminating weather and meteorological information and forecasts to farmers play a crucial role in effectively planning agriculture activities. Climate services allow farmers to prepare for drought or heavy rainfall events which can help save crop damage. This approach provides location-specific weather short-term and long-term forecasts to farmers by SMS, and USSD codes, through an Android app or call centre with a toll-free hotline. SMS is a common tool for sending out weather information to large groups of farmers. Below are examples of websites that provide daily, weekly and seasonal weather forecasts:
   - Kenya Agricultural Observatory Platform For example, County meteorological officers in Kenya send bulk SMS messages of weather forecasts to farmers within their community.
   - In IGAD countries, the IGAD Climate Prediction and Applications Centre (ICPAC) produces Season Forecasts every quarter.
   - In Uganda, the Uganda National Meteorological Authority (UNMA) releases Seasonal Rainfall Outlooks. These can also be accessed via the USSD system by dialling *201#.
   - Ignitia This is a subscription-based and customisable platform that sends out location-specific (1-3 Km) and real-time (12 to 48hrs) weather SMS messaging services allowing farmers to prepare for drought or heavy rainfall events. It's also available as a mobile phone app called Iska to subscribers.

3. **Early warning systems for Invasive Pests:** Dissemination of information about the occurrence of pests and diseases due to changing climatic conditions and its management practices help better prepare and respond on time. Agro-advisory services can help save crop damage. For instance, the damage caused by the Fall Armyworm (FAW) *Spodoptera frugiperda* is particularly worse under low-input smallholder production. Since, FAW is relatively new in East Africa, farmers and extension workers need to have immediate access to key information on the pest's behaviour, on how to reduce infestations and crop damage, and how to adjust the agroecosystem and ensure sustainable management. Hence, monitoring and early warning mechanisms are of central importance.
   Here we use the case of the case of the Fall Armyworm Monitoring and Early Warning System in

Africa [Buchaillot *et al.* 2020], one of the two primary early warning systems available in Eastern Africa.

- Fall Armyworm Monitoring and Early Warning System. This is available on the web and as a Mobile app. It consists of FAW data and maps that provide valuable insights on how FAW populations change over time with ecology, to better understand its behaviour and to help guide best management practices. The app offers IPM education, a Digital library, Chat options to share experiences and expert resources.
- e- Locust system. [Cressman *et al.* 2016]

4. **Pest and disease identification tools:** The high incidences of pest and disease infestation often trigger farmers to routinely apply chemical pesticides to protect their crops posing a health risk both to the consumer and the farmer due to mishandling or misuse. To reduce pesticide misuse among smallholder farmers, an integrated pest and crop management (ICM) approach is important. However, it is knowledge-intensive and requires early detection which can be achieved through routine monitoring of crop health and disease surveillance using digital tools such as the PlantVillage Nuru mobile phone app.
    - The PlantVillage Nuru App. Through a set of simple procedures, this app scans, diagnoses, and detects disease and pest infections on crops and has been efficiently working to help maize, potato, and cassava farmers in Kenya, Tanzania and Uganda [IITA 2021]. The PlantVillage app is a publically supported, and publically developed application that uses a digital assistant to help farmers diagnose crop disease in the field, without an internet connection [Kreuze *et al.* 2022]. The app uses Google's Tensorflow machine-learning tool and a database of images collected by crop disease experts across the world. The app is based on extensive research comparing the accuracy of machine learning models to human experts and extension work. The app can (i) Determine presence of diseases symptoms or pest on the crop (CMD, CBSD and CGM-damage on cassava; bacterial wilt, late blight and early blight on potato; FAW on maize, (ii) Gives feedback (real-time), (iii) Shows you the symptoms of the disease/symptoms it has recognised (teaching tool), (iv) Give you advice on management and/or control practices for the disease/pest it has recognize Nuru app and (v) Diagnose healthy crops. By determining which crops are healthy, farmers can propagate cuttings from disease-free plants. The use of clean planting material cuttings often results in higher crop yields.

5. **Weather-Based Index Insurance:** Some insurance companies offer weather-indexed insurance products that compensate crop and livestock farmers for partial or total loss in yields caused by prolonged drought or floods. Both private and public institutions are increasingly offering agricultural insurance products. Below are some of the companies that offer agricultural insurance in Eastern Africa
    - Agriculture And Climate Risk Enterprise (ACRE Africa) Acre Africa provides several crop and livestock insurance products including Area yield index, Soil Moisture Index Insurance, Picture-Based Insurance, Weather Index Cover and Fodder crop cover. It can be accessed using the Digibima App
    - One Ace Fund Re. One Acre Fund offers enrolled farmers insurance coverage against unexpected weather events.
    - Pula. This is an agricultural insurance and technology company that designs and delivers agricultural insurance products to protect smallholder farmers against a wide range of climate risks including drought, excessive rainfall, pests and diseases, and several other perils that negatively affect their yields. The company has a presence in Kenya and Uganda.

6. **Water management tools:** These soil moisture and nutrient monitoring tools ensure efficient utilization of water resources and improved productivity in semiarid areas and are suitable for

smallholder irrigation farmers. Over or under-watering reduces crop productivity and reduces potential economic gains to be made from irrigation. For instance, over-irrigation reduces the efficiency of fertilizers, increases fuel and labour costs and potentially results in low crop yields and, therefore, a reduction in income. It also leads to soil degradation, salinization and the potential occurrence of pests and diseases. Such smart technology can positively adjust farmers' irrigation regimes resulting in more sustainable use of water and improved yields [Mdemu *et al.* 2020]. These include:

- Virtual Irrigation Academy (VIA) tools: The moisture monitoring tools comprise a moisture sensor buried in the soil (about 30-40 cm), a "wetting front detector" that shows the amount of nitrate in the soil and a "Chameleon Sensor" that displays the level of soil water suction using blue, green and red lights as information signals - when the reader turns blue it means there is a lot of moisture in the soil, the farmer does not need to irrigate; when it turns green, it means there is still adequate moisture in the soil, however, should plan to irrigate his/her crop in the 3 or 4 days; and when the reader turns red, it means that the farmer should immediately irrigate the crop.
- Sunculture: This platform offers solar irrigation systems with data feedback loops monitoring water usage.

7. **Soil Testing and Nutrient Management tools**: Precision nutrient management through selecting the right source, amount, place, and application method will help achieve higher efficiency, particularly nitrogen fertilizers, thereby mitigating greenhouse gas emissions through reduced N_2O emissions [Hassan *et al.* 2022]. Below are some of the available digital tools that support fertilizer use
    - The Smart Nkunganire System (SNS) tool in Rwanda: This tool delivers tailored fertilizer recommendations for six high-priority crops—cassava, maize, wheat, potato, rice, and bean—to extension agents and smallholder farmers in Rwanda through the country's existing SNS digital supply chain, which allocates agricultural subsidies to farmers for purchasing seeds and fertilizers. The fertilizer recommendations are site-specific to farmer circumstances and contexts. Being suited to local conditions, such site-specific fertilizers not only enhance soil health and increase crop yield and quality but also are resource-efficient and environmentally sustainable. The Smart Nkunganire System is continuously digitizing more services beyond the fertilizer input subsidy program to include all major agro-inputs, extension services, loan facilities, payment services, insurance services and output markets [Stokke 2019].
    - The Fertilizer Optimizer Tool by CABI. This free Android app helps farmers to efficiently use fertilizers and save money. The app can work offline and gives crop and site-specific application rates including recommended integrated soil fertility management (ISFM) practices.
    - Soilcares: This platform offers soil testing services with sensors to provide soil fertility (macro- and micronutrients) feedback remotely and quickly.

8. **Greenhouse gas reduction services:** This involves using technology such as sensors, drones, and satellites to collect data on soil, crops, and weather conditions. This information can be used to optimize the use of inputs such as fertilizer, water, and pesticides, reducing waste and increasing efficiency. The placement of fertilizers also has a great impact on the soil processes involved in gaseous emissions. One such technique is fertilizer deep placement (FDP) which may prove as a saviour in reducing greenhouse gas emissions from soil. Platforms such as Acorn by Rabobank connect farmers to carbon credit markets hence rewarding farmers for adopting practices that sequester carbon in the soil, such as composting and no-till farming. This can provide farmers with an additional income stream while promoting climate-friendly practices.
    - Z'Wardy platform. This is a mobile phone app managed by Solidaridad Network and is cur-

rently available in Kenya and Uganda. The extension staff of Solidaridad maps a farmer's crop fields using the Open Data Kit (ODK) Collect app and issues a QR code ID. Satellite imagery is then used to monitor crop health and track the adoption of climate-smart farming practices. Farmers receive tangible rewards (farming tools and inputs) as an incentive for adopting sustainable farming practices. They also receive location-specific and real-time agronomic advisories like planting time to prevent low yields. Use of satellites to observe the plant's greenness and biomass every two weeks and analyse the status of vegetation using the Normalised Difference Vegetation Index (NDVI) to assess crop health, predict crop yields, flowering time and maturity date.
- Acorn By Rabo Bank: Acorn trains and supports smallholder farmers to transition to agroforestry. Once the trees have grown and captured enough carbon from the atmosphere, Acorn issues carbon removal units that are sold to companies. 80% of the sales price flows back to the farmer, 10% goes to local partners and 10% is for Acorn. Acorn has projects in Kenya, Uganda and Tanzania.

9. **Marketing and Market Information services:** Farmers with market access are more likely to adopt CSA. These platforms, most of which are Mobile apps provide farmers with daily (real-time) market prices. On some market platforms, farmers can list and sell their produce or even buy agro-inputs. Below are some examples
   - Mkulima Young. This is an online marketplace for farmers.
   - Nampya Farmers Market. This is an integrated mobile-enabled trading platform that connects them to stable markets and fair prices
   - Farm Pass. This platform provides a digital marketplace for buyers who are looking for sustainable sources of quality produce at favourable market prices and for smallholder farmers looking for reliable markets and fair prices. Farm Pass brings together various agri-sector stakeholders in one agricultural marketplace, amplifying the collective positive impact on farming communities. It brings the benefits and security of digital payments to smallholder farmers in India, Kenya, Uganda, Tanzania and beyond, giving them access to the digital economy.
   - Esoko Market Place in Rwanda. The platform provides market information prices of agricultural commodities in the different markets in Rwanda.
   - Kenya Agricultural Marketing Information Systems (KAMIS). A web-based platform that provides real-time market (wholesale, retail, and farm-gate) prices for more than 150 agricultural (crop, livestock, and fisheries) commodities in atleast five markets in each of the 47 counties of Kenya.
   - Producers Direct. This platform has three tools. 1) Farm Direct that connects farmers to market, 2)An On-line shop selling honey directly from producers and Croppie, a picture-based yield estimate technological solution designed to support decision making of smallholder coffee producers. It leverages AI to quickly estimate coffee yield and provides tailored recommendations based on the analysis of farmers' practices.
   - Digi-Soko: The platform connects you to vendors of groceries in five markets around Nairobi, Kenya. It allows to place your orders of any farm produce and it will be delivered to you in less than one-hour by Soko Kijiji.

10. **Farm Mechanisation services:** Mechanisation reduces drudgery by saving on labour and time and enables women to establish large acreage of crop fields resulting into timely planting, spraying, and harvesting and hence higher yields. Such technologies also reduce production cost and thus increase farmer's revenue. However, most agricultural equipment is expensive and out of reach for an individual smallholder farmer. However, when farmers are organized in cooperatives, innovation platforms or connected to digital platforms, machinery can be shared.
    - Agrishare in Uganda: This platform allows farmers to lease land, hire equipment such as

tractors, trucks/lorries and portable milling machines, corn shelling machines, or irrigation equipment. This approach promotes the effective utilisation of community assets. Agrishare works similarly to Uber and AirBnB.
    - Hello Tractor: The platform connects farmers to low-cost leasing services for increasing access to agricultural mechanization services such as ploughing, ridging, planting, weeding or harvesting.
11. **Agricultural e-financial services:** Farmers with access to credit are more likely to adopt CSA. This category of digital innovations facilitates financial transactions between farmers and other value chain actors. Below are some of the digital platforms providing financial services to farmers in Eastern Africa.
    - Akello Banker: The platform enables smallholders and SMEs to access important and life-saving collateral-free services such as access to farm inputs and extension services on credit. It also links farmers to input and output markets.
    - MKash: This is a financial inclusion system that supports farmer registration (e-KYC, e-Voucher and e-Commerce). The system is being used by MAAIF in Uganda to issue subsidized inputs to farmers. Enrolled farmers can directly order for farm inputs which they subsequently redeem on delivery. MKash u uses the Web, USSD, Mobile app and Point of Sale machines through MKash agents.
    - Yo Uganda Limited ("Yo!") Pay. This platform allows farmers to directly interact with buyers at sub-national, national and international levels. Farmers can also directly engage banks, insurance companies, agro-input suppliers, agro-machinery equipment, agrochemicals, irrigation technologies plus veterinary services. The Yo! Pay platform not only improves access to services but also reduces the cost to the farmer, and improves the effectiveness of service delivery.
    - Agri-Bora. This platform uses SMS, USSD, and mobile payments along with advanced smartphone applications and analytics fueled by Earth observation satellite data. Agro-input dealers received orders and payments from farmers through the platform. AgriHUB owners are also able to access credit but also maintain records of all the transactions within the app.
    - Apollo Agriculture: This platform provides farmers with financing to acquire high-quality farm inputs from its digital store. The farmer then picks up the ordered input at the agro dealer in their nearest village. In addition, farmers receive training in good agricultural practices while those who purchase inputs on credit automatically receive agricultural insurance to protect their harvest from climate hazards. This app is available in Kenya and Zambia.
    - Mobile Money Platforms: These are mobile phone-based money transfer services, payments and micro-financing services offered by telecom companies. They facilitate financial transactions between farmers and other value chain actors such as traders, aggregators or processors. Examples include M-Pesa in Kenya, MoMo in Uganda, MoMo in Rwanda and Airtel Money in Uganda, Kenya and Rwanda.
    - Agriwallet: This platform allows farmers to save and borrow to purchase drought-resistant/quality inputs with mobile money via mobile phones.
    - MobiGrow: This is a mobile-based digital credit facility allowing smallholder farmers to access agribusiness loans, savings, insurance, market information and training. Farmers sign up through M-PESA. It's a product of KCB and is available in Kenya and Rwanda. Farmers access it by dialing *225# from their mobile phones.

12. **Digital solutions for Agro-input supply and use:** Below are some of the digital platforms that sell agro-puts to farmers in Eastern Africa.
    - Ezzy Agric: This platform is available on the web and as a phone app. Farmers can order pesticides, seeds and farming equipment or tools. It has a partnership with the telecom

service provider, AIRTEL Uganda and can also be accessed via the My Airtel App.

13. **E-Learning and farm management platforms:** Digital learning reaches more people faster and at lower cost than traditional extension. Below are some of the platforms dedicated to training of farmers and farm management:
    - DigiCow Dairy App: The mobile-based phone app gives the farmer access to verified, reliable and timely information on animal husbandry (milk production, milk sales, health, breeding and feeding information) from wherever they are. The App provides a 24-hour service training room where farmers can listen to audio and video training content or written content on demand. The app also has a real-time Chatroom where farmers get to interact and exchange ideas and experts within the group can assist. The App enables farmers to digitize their farm records and has an inbuilt analytics system that provides real-time reports to the farmers. In addition, it sends a notification to the farmers regarding important dates for their cows.
    - Shamba Pro: The app helps a farmer to schedule, allocate and approve farm tasks with Farm Calendar to keep track of the performance of farm workers. Keep different types of non-financial farm records e.g. feeding, breeding, milking or health records with Production Records. Track records of a specific animal, flocks of birds, crop fields and paddocks. Use Financial Records to approve and monitor financial transactions on the farm to ensure integrity, transparency and accuracy. Control and manage your Farm Store digitally in real-time. Check the financial health of your farm business at any time with Farm Reports.
    - M-Shamba: This platform supports digital learning on agronomy, climate-smart interventions and food safety to the farmers through the Interactive Voice Response (IVR) service, USSD and interactive SMS. The platform also connects the farmers to the experts in the field through the Cloud-Based Virtual Call Centre for real-time and personalised support.
    - Digital Green: This platform partners with Government extension service providers to produce and air videos that are used to train farmers about CSA. It uses a community-led approach for digital content production and in-person farmer training involving the creation of agricultural videos enacted by local farmers. In Africa, they have a presence in Kenya & Ethiopia. Digital Green has a multi-lingual Artificial intelligence (AI) powered chatbot which acts as both a multi-media (text, audio and video) content retrieval and delivery mechanism to both receive and push messages for customised climate smart messages via the Telegram App.
    - Viamo Platform: This is an IVR service provider in the region (formerly known as the 3-2-1 service). Viamo provides the following services (i) conducts digital training for rural communities using basic phones., (ii) Digital Marketing through automated phone calls (iii) Digital Campaigns to foster behaviour change and (iv) Digital Surveys to assess the perceptions of mobile phone subscribers. Farmers can also use IVR systems to ask questions and get advice from extension workers. IVR technology significantly improved the knowledge of farmers who had not been exposed to training on biosecurity in Uganda [Dione et al. 2021]. IVR enables to remotely deliver agronomic training to millions of farmers at ago. Tailored content can also be developed for a specific value chain.
    - Farm Radio International. Farm Radio International (FRI) has partnerships with radio stations that air Programs, Spot Messages and host Talkshows specifically for farmers. Among the services offered by FRI is (i) training of radio broadcasters to disseminate high-quality and factual information (ii) developing radio scripts, drama, backgrounders and other information resources for broadcasters (iii) designing training programs on agriculture and rural development and (iv) disseminate information to farmers through radio. FRI also has a customized interactive tool called "Uliza". This tool enables listeners to communicate and exchange information with their radio station quickly, easily and free of charge. It can be used for conducting polls (Beep2Vote), interviewing farmers (Beep2Vox) and providing

weather information upon request (Beep4Weather).
- The Cassava Seed Tracker: This platform links cassava seed producers with regulators and farmers.
- Akilimo: This tool provides site-specific recommendations of good agronomic practices to optimise the productivity and profits of cassava.
- Farm Biz AfricaFarmBizAfrica. A website that provides news, stories and information on breakthroughs in seeds, pest control and farming methods, new markets, and high-return business formulas.
- KTN Farmers Tv. A 24-hour TV channel specialising in agricultural content through feature documentaries, news, demonstrations videos and talk shows. This Tv can also be accessed via Facebook and YouTube
- Shamba Shape Up. This is a reality Tv show that provides educational agricultural extension and key climate information to farmers in an entertaining manner. The TV shows include the soap drama Makutano Junction, the children's educational series Know Zone, and the Don't Lose the Plot, which aims to encourage youth into agribusiness.
- The MAAIF e-Extension System in Uganda This platform showcases agricultural training videos in local languages and provides weather advisory and information on crises and disease outbreaks in Uganda.
- Arifu: This is customised and subscription-based platform that offers training courses on different topics to farmers.

14. **Bundled products and services:** In some cases, it has been reported that providing a package of services yields better results than delivering a single product. So, bundled CSA TIMPs are increasingly becoming common on the market. Examples of these include:
    - ShambaShield. This comprehensive package offers (1) climate and financial information through Shamba Shape Up; (2) the financing needed to enhance maize-mixed farming system resilience through a financial institution and enabled by climate-smart credit rating; and (3) a safety net through the insurance product (risk-contingent credit). All these services (financial, credit, insurance, and literacy) have been reported to improve climate risk management among smallholder farmers. ShambaShield adopts a comprehensive social inclusion strategy, ensuring that youth, women, and men have equal opportunities to access and benefit from these innovative bundles.
    - m-Omulimisa: This is a USSD (*217*101#), web-based and mobile app platform that offers extension services, real-time weather and market information, micro-loans, agriculture insurance, marketing support, and mobile learning on a commercial basis (Market information UGX 2,000 per month, or 20,000 per year; location-based (accurate up to a 9km radius) weather updates UGX 4,000 per month or UGX 40,000 per year). These services are primarily delivered through a combination of mobile-based tools and a network of commission-based agents. This app enables farmers to exchange information with extension officers in indigenous languages. Farmers ask questions using text messages.
    - Esoko: This platform uses mobile and web platforms to link farmers to agricultural value chain actors such as input dealers, financial institutions, and insurance service providers. Esoko's platform distributes digital content ranging from agricultural market prices, weather forecasts, climate-smart agricultural advisories and agronomic advisory content [Nii-Koi G. 2021]. Its hyper-localised content is delivered to farmers' mobile phones using SMS, IVR, and voice messaging in local languages and call centres.
    - Digi Farm: The platform can be accessed through a USSD channel *944#, a smartphone application and has call center support. The platform offers soil testing services, quality inputs, insurance products, mechanization and digital extension services. Additionally, farmers can access credit for these services and as a result, invest in improving their production and yields. Post-production, farmers are connected to buyers on the same

platform. Buyers can source directly from smallholder farmers and pay them through an integrated M-Pesa wallet. The buyers can also access working capital to pay farmers cash on the spot.

- Famunera: This is a web-based platform that sells agricultural produce but also offers credit to its suppliers (farmers). The platform guarantees traceability for all products listed on its website.
- Shamba Pride: This platform can be accessed via Mobile App, USSD Dial *483*199# and Web platform and it offers (i) training to agro-dealers to become more professional, and profitable and offer superior services to local farmers, (ii) sell inputs (Seeds, Fertilizers, Agrochemicals, Animal feeds, Mineral Supplements and Farm Tools to the agri-retailers and farmers), (iii) Links farmers to medium and large offtakers, (iv) farmers and agrodealers can access short term working capital and credit to expand their agribusinesses (v) digital Extension: Farmers access expert crop and livestock advisory at comfort of their mobile phones (vi) Soil testing: Farmers request for soil testing testing at comfort of their mobile phone and have soil sample collected, analyzed and receive recommendations (vi) Inventory and financial management (vii) Inputs Insurance
- iShamba : Famers can call and speak to agricultural experts to ask any question related to crop and livestock, market prices or weather.
- UjuziKilimo: Provides farm-specific recommendations (fertilizer, agro-weather advisory) based on data collected with the Ujuzihand-held soil-testing device, weather forecasts and in-house data analytics. Device captures soil characteristics, topography and environmental data which is analyzed by experts to provide actionable recommendations.
- Tulaa: This is a marketplace for smallholder farmers, providing them inputs, credit, agronomic advice and market linkages. Farmers are connected directly to buyers hence relieving them of exploitative brokers. Tulaa can be accessed via SMS using USSD codes, call center and mobile app in Kenya.
- Hinga-Worore: This mobile-pone based app provides farmers with the following services (i) Weather and Crop calendar, (ii) cure and feed your livestock, (iii) Agrimarket place, (iv) e-nutrifood and (v) Fall Army worm monitoring and early warning system. The app is available in Rwanda and contains information in Kinyarwanda, English and French.

What opportunities do digital innovations bring to CSA?

Several factors have been reported to limit the utilisation of digital technologies in African agriculture, but rather than focusing on the challenges, this paper will propose opportunities that can increase the use of digital solutions in CSA. These include:

1. Increasing digital literacy levels for both women and men especially those above 35 years. Community-based adult educational programs offer an opportunity for education without the restrictions of time or location. So, by improving access to short community-based adult learning courses from vocational institutes at the certificate level, the literacy levels of farmers can be improved. To avoid disempowering those who cannot afford mobile phones, a deliberate effort by all sector players to ensure access to digital information is key.
2. Increasing access to both basic and internet-enabled smartphones. This could done through the provision of smartphones on contract or credit to enable the farmers to pay for the phone over 1-2 years. Increased access to mobile phones will stimulate and improve farmer information-seeking behaviour.
3. Increased coverage of rural areas with mobile and internet coverage by telecom service providers. This will require investment in infrastructure.
4. Developing products that reduce the cost of internet mobile broadband and bandwidth to make it more affordable. One option could be done by zero-rating websites and mobile apps that provide agricultural information to farmers in rural areas. Access to the internet can en-

hance adherence to agricultural production protocols.

5. Engagement of youth to provide low-cost community-based extension services on a commercial basis. This will not only create jobs but will attract the youth to agriculture by participating in the upstream activities of the value chain. This will also reduce the current low extension worker-to-farming household ratio of 1: 1,800 for Uganda, 1:1078 for Kenya and 1:136 Rwanda [MAAIF 2019; Chibi 2023; Mabaya et al. 2021].
6. Access to real-time market price information improves negotiation skills and better decision making resulting in improved household income.
7. Formalizing offtake arrangements increases farmer motivation to the digital services.

How can the adoption of digital innovations reduce the risk associated with climate change among smallholder farmers?

Through increased access to climate-smart practices, facilitating knowledge exchange, and offering critical tools, digital tools empower communities to not only adapt to climate change but also thrive in the face of these environmental challenges. Use of digital tools to increase the reach of extension services will support the adoption of proven climate-smart technologies and innovations while tapping the full potential of multistakeholder partnerships.

1. The use of digital technologies to access climate information plays a pivotal role in helping communities adapt to the challenges posed by climate change [Mulwa *et al.* 2017]. For instance, use of climate services was reported to increase the adoption of multiple cropping practices by 6.8% and water management by5.6% respectively [Djido *et al.*, 2021].
2. Use of digital tools facilitates farmers to independent carryout real-time disease and pest monitoring systems also aid in the early detection and management of threats exacerbated by climate change.
3. Digital platforms offer a space for farmers to share their experiences and learn from each other, fostering a sense of community and cooperation. The platforms equip individuals and communities with essential knowledge and tools to navigate the ever-evolving climate patterns
4. There is a need for multistakeholder partnerships among the private sector, Government institutions, farmer cooperatives, non-profit organizations, academic institutions and the international community to disseminate these proven digital technologies for utilisation by many farmers. Currently, only a few farmers have access to these TIMPs.
5. There is a need for continuous digital literacy training programs in rural areas for both men and women. More capacity-building efforts are needed especially for women. Most digital tools seem to be gender sensitive as they address some of the constraints women face in accessing conventional extension services such as time. However, those who cannot afford mobile phones tend to be left out.
6. There is a need to boost public and private investments, especially in infrastructure, product development and marketing to suit the various needs of farmers.
7. There is a need to continuously improve the digital CSA TIMPs to make them more user-friendly, and light on data.
8. There is a need for fair pricing, honesty and transparency during marketing of the digital services to increase trust and buy-in by end users.
9. Increased coverage to suit the local situation based on the agro-ecological zone is also paramount.
10. There is a need to develop inclusive strategies and gender-sensitive action plans for scaling most of these innovations into wide use.

Conclusion

Our review brings to the limelight several digital technologies and innovations available for use by farmers in Uganda, Kenya and Rwanda. The listed digital technologies have been reported to have contributed to increased farm productivity and adaptation to climate change or mitigation. The potential of digital tools once explored, can empower smallholder farmers to address climate risks. Although a large number of the platforms require an internet-enabled smartphone, some of them are low-cost and are accessible to farmers who even don't own a personal radio or phone but simply through community-based clubs or digital connectors. However, increased investment from national and international organisations, alongside public and private institutions, is crucial in facilitating the widespread utilization of digital agriculture tools. The is a need for continuous training of farmers in not only the use of digital tools but also in the adoption of the available CSA technologies and practices at scale. Further research is necessary to solidify the empirical evidence base specifically documenting the direct contribution of digital technologies to enhanced farm productivity and resilience while also contributing to climate mitigation efforts where applicable would be highly valuable for future policy and development efforts.

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Reducing Carbon Footprint from Food Losses Using Sustainable Cooling Technologies

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Abstract

Fruits and vegetables play important roles in maintaining a healthy life. They are highly perishable and require cooling technologies to extend their shelf life which is seldom available in many Sub-Saharan Africa countries. Green House Gas (GHG) emissions from food supply chain is a major contributor to global warming with carbon dioxide (CO_2) emissions from food loss and waste (FLW) accounting for about half of the global GHG emissions from the entire food system. Some of the emissions results from poor storage and handling techniques. Reducing FLW using smart postharvest technologies is a key strategy for reducing food loss emissions. Low energy cool barn was constructed from locally available materials and a solar cold powered room coupled with a remote monitoring system. The potential of the cooling technologies in reducing quantitative postharvest losses in tomatoes and garden eggs were quantified. After 15 days of storage, weight loss in garden was 20%, 56%, and 71% in solar powered cooler, passive cooler, and control respectively. Reduction in weight loss in garden egg was 39% after 8 days and 71% after 15 days. The results will help smallholder farmers and fruit marketers to adopt passive coolers and solar coolers for sustainable food loss management.

Keywords: carbon footprint, climate adaptation, food loss, sustainability,

Introduction

Climate change has become a global phenomenon that poses serious threat to human live and the environment. Although climate change has diverse consequences on human and the environment, its impact on agricultural productivity is high and it has exacerbated food insecurity especially in the low-income countries like sub-Sahara Africa even though they have contributed little to climate change (Cervantes-Godoy *et al.*, 2013; Ringler *et al.*, 2010. Tol, 2009). Erratic rainfall patterns, severe flooding droughts and increase in pests' pressure are among the harmful effects of climate change that has affected smallholder farmers in developing countries causing a serious decline in their productivity and reduction in their real income (Mulwa *et al.*, 2017; Kulp and Strauss, 2019). Small-holder farmers have developed adaptation strategies to survive the onslaught but have struggled due to their conventional practices and economic vulnerability. Strategies adopted by farmers in the developing countries varied and, in some cases, farmers have used existing knowledge with a little degree of success (Smit and Skinner, 2002; Elum *et al.*, 2017.

Food postharvest loss in Sub Saharan Africa is very high representing about $ 4 loss annually (Worl Bank, 2011). This constitutes a major impediment to achieving food and nutrition security in the region. The losses affect the livelihoods of the people as well as their life expectancy (Srivastava, 2018). This has led to heightened hunger in most of the countries. Postharvest loss is also a major contributor to greenhouse gasses thus playing a major role in global warming (Ntinyari, W. and Gweyi-Onyango, 2021). About one-tenth of global GHG emissions is associated with food loss and waste. It also represents a waste of resources that have been used to produce food that is not consumed. Reducing post-harvest food losses is thus an adaptation approach for mitigating impact of climate change as it can increase the availability of nutritious food without increasing land cultivation and inputs while at the same time cutting down greenhouse gases (Arias Bustos and Moors, 2018). Inadequate handling and storage facilities have been identified as the major challenge facing postharvest management in Sub Sahara Africa (Mulwa *et al.*, 2017) The development and deployment of innovative technologies for handling, storage, and marketing of crops are crucial to reducing food losses in these countries as shown by experiences from other developed nations of the world. Adequate storage facilities and solar-powered cold chain facilities can extend the shelf life of durable and perishable crops which will lead to increased income and improved livelihood for farmers (Benyam *et al.*, 2021). Therefore, reducing postharvest losses can guarantee food security and at the same time mitigate the effect of climate change in Sab Sahara Africa.

The carbon footprint (CF) of a food product4 is the total amount of greenhouse gases (GHG) emitted throughout the life cycle of that product, expressed in kilograms of CO_2 equivalents (Nabipour Afrouzi, 2023). This encompasses all GHG emissions of the agricultural phase – including the emissions related to the production and transport of all inputs, as well as the emissions due to on-farm energy use and non-energy related emissions (such as CH_4 and N_2O) from soils and livestock. The carbon footprint also includes the GHG emissions related to the processing of food, delivery to a point of sale or use location, and to the consumption as well as emissions from waste disposal (Sharber, 2023). The concept of Climate-Smart Agriculture (CSA) was introduced as an approach to help farmers and other stakeholders in the food systems respond effectively to climate change with the view of mitigating its impact. CSA approach centres on increasing agricultural productivity and incomes sustainably, resilience in adapting to climate change and reducing greenhouse gas emissions. Agriculture is a major source of greenhouse gas emissions including methane (CH_4), nitrous oxide N_2O, and carbon dioxide (CO_2) (Matteoli). Mitigation can often be a significant co-benefit of actions to strengthen adaptation and enhance food security, and thus mitigation action compatible with national development priorities for agriculture is an important aspect of CSA (Boyd, 2022). This study demonstrates the application of sustainable cooling solutions as plausible climate adaptation approach for mitigating PHL and thus reducing the carbon footprint of vegetables.

Materials and Methods

Construction of Low Energy cool barns (LECB)

Low energy cool barns (a form of passive cooler) of dimensions 2.9 m x 2.0 m x 2.0 m were constructed with burnt brick, mat and galvanized sheets. The structures have a total brick wall height of 1.2 m and a woven mat upper wall of 1 m with a trench of about 20 cm around the base filed with riverbed sand. Construction considerations were based on total brick wall area exposed to evaporative cooling. The structures were constructed such that 50% of the brick wall was submerged in the soil while the control does not have a sub-surface wall (100% wall on the ground surface (figure 1). This was so that the structures could have heat transfer from the inside of the structure through the brick wall into the surrounding padding materials (river-bed sand) and, then to the atmosphere as water evaporate form the surrounding padding media (Figure 1). The roofs were insulated to reduce heat buildup in the structure. The was done by first by putting a layer of white tarpaulin, followed by a layer of 20 mm fiber glass and corrugated galvanized roofing sheets.

Figure 1. Low Energy Cool Barn

Construction of Solar Powered Cold Room (SCR)

A 250 kg capacity solar cold room for the storage of fruits and vegetables was constructed in Ilorin, Nigeria using the self-chill model. The solar powered cool room consists of three units namely, the electrical units, the cooling unit and the storage unit. The electrical unit consist of five (8) solar panels (PV) connected in parallel through a charge controller to four (4) units of 230Ah capacity tubular battery. The cooling unit has a water chiller bath (91 x 71 x 73 cm) insulated with 100 mm polyurethane panel with four (4) compressor of 75 W DC capacity each having evaporator plates. A 9 W-DC water pump is installed to transfer cold water from the water chiller into the cold room through the heat exchanger 30 W. The storage chamber (~ 9 m^3) houses set of racks on which fruits crates are arranged is made of 100 mm thick polyurethane sandwich panel.

To prevent the system from shut down and improve cooling performance, the electrical system is divided into the primary and secondary system. The primary system comprises of the solar PV electrical units having five (5) PV panels of 1700 Wp capacity and four (4) cooling units connected in parallel with 60 mm twin cable connectors to a 100 A Posmith Dc breaker and 600 vdc protector (positive and negative) terminals to an 80 Amp felicity MPPT charge controller. It has three sets of 230 Ah Eastman tubular batteries connected in parallel surge to the battery terminals of the 80 A charge controller in a (12 Vdc circuit). A second charge controller (40 Amp SMC PWM) was installed as the load point limiter to the felicity charge controller load terminals to make provision for the load connection. The four (4) cooling units of 75 W capacity each having evaporator plates were connected in parallel to the load point of the 40 A charge controller using 2.5 mm four cores flexible cable with each line equipped with a 15 A fuse holder and fuse. The evaporator plates were submerged inside a 480 litres capacity insulated water chiller bath for ice production and thermal storage.

The secondary system consists of the storage chamber installed with a heat exchanger (20 W LG evaporator AC fan) inside having a DC water pump of (70 W - 12 Vdc) controlled with a 12 Vdc thermostat installed to circulate cold water from the water chiller bath through the heat exchanger inside the storage chamber, the heat exchanging process transfer the coolness from the water into the storage chamber. The pump is connected to the bottom side of the water chiller bath lifting water through the piping network to the evaporator through a 0.15 mm hoses plumbing fittings. Power supply to drive the secondary systems is supplied from a dedicated 700 Wp solar PV panel and a 230-ah battery. The circuit diagram showing the connection of the various components is shown in Figure 2 while the back view of the solar powered cold room showing the cooling unit and the battery arrangement is shown in Figure 3.

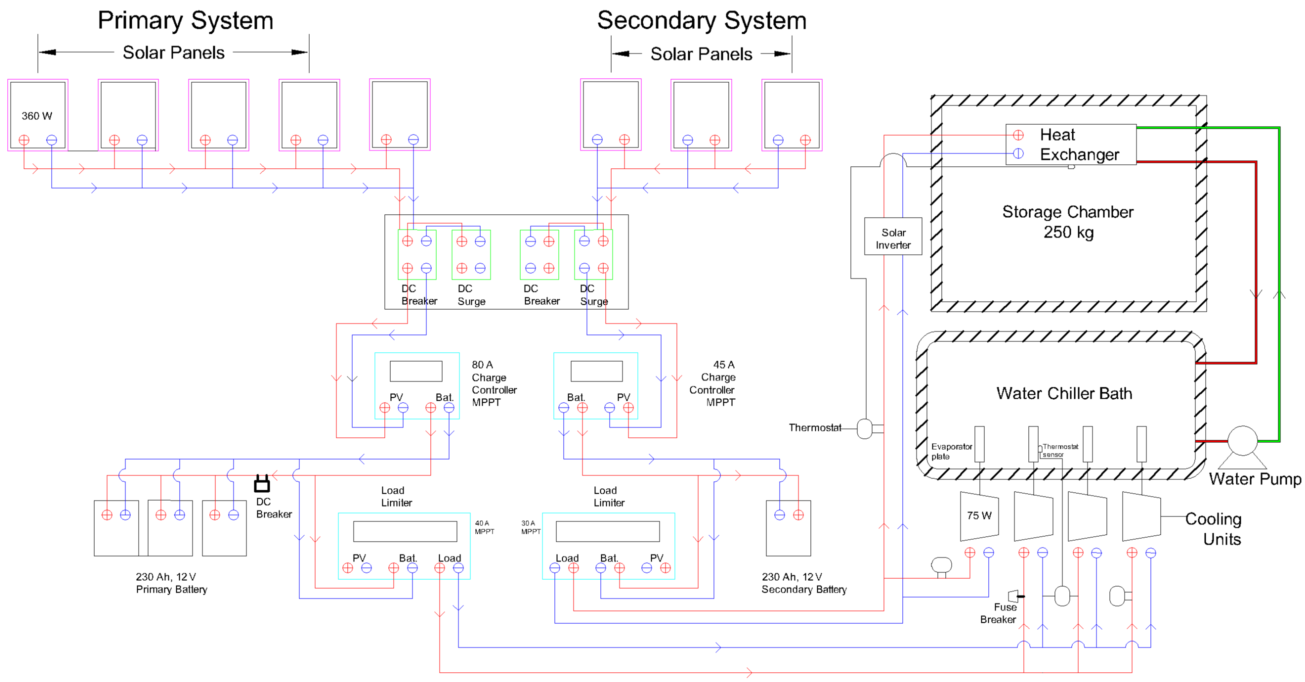

Figure 2. Circuit Diagram of the components of the solar cold room

Figure 3: The Back view of the solar cold room showing the cooling unit and battery system

Shelf live study

Garden egg (*Solanum melongena L*) was procured from a farm near Lasoju in Asa LGA of Kwara State Nigeria and transported in ventilated plastic crates to NSPRI campus. The garden eggs were sorted washed and put in a clean plastic crate and allowed to drain before after which 10 kg were weighed into the plastic crates. The plastic crates with garden eggs were then placed into the storage structures (four (4) crates) each (Figure 4). Four crates were arranged under a shed as control. Before introducing the garden eggs, the LECB were watered until the riverbed sand around the structures were sufficiently moistened while the thermocouple in the SCR was set at 15 ^{0}C. Hobo data logger (Onset Computer Corporation, USA) was placed in the plastic crates to monitor the temperature and relative humidity while the ambient data was recorded using a Kestrel (5000AG) weather station (Nielson-Kellerman Co., USA). The environmental data were recorded hourly, and the daily average was computed. Samples were taken at the first day of the experiment for quality analysis. Colour changes in the stored garden eggs was measured with a colorimeter (CEILAB CEIL-CH display mode). The sampling was reported every three days till the fifteenth day. The storage experiment was conducted from September 26 to October 10, 2024.

Figure 4: Arrangement of the plastic crates in the LECB and SCR

Quality Evaluation

Sampling was conducted every 48 hours throughout the storage. The quality parameters that were monitored include weight loss, colour change and total colour index.

Percentage weight loss was determined using the gravimetric method. Each crate was weighed in (kg) using a Camry digital weighing balance (± 0.01 accuracy). The percentage weight was calculated using equation 2.

$$WL\,(\%) = \frac{W_i - W_{i+1}}{W_i}\, x\, 100 \qquad 1$$

where: WL = % weight loss, W_i = initial weight of tomato in crates, and W_{i+1} as apparent weight for subsequent sampling.

The colour of the vegetables was determined using Colorimeter (Fru WG-10Q) and measured in terms of L, a, b. the total colour index (TCI) and total colour difference (ΔE) were estimated using equations (3 & 4) as described by Concepcion et al., 2021.

$$TCI = \frac{2000 * a^*}{L\sqrt{a^{*2} + b^{*2}}} \qquad 2$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^{*2} + \Delta b^{*2}} \qquad 3$$

Where: TCI = Total Colour difference index, ΔE = Total Colour change magnitude, ΔL* is the difference in lightness, Δa* is the difference in ripe-greenness, Δb* is the difference in yellowness.

Statistical Analysis

Data collected were analysed using pandas (2.0.3) and matplotlib-inline (0.1.6) packages on Python® 3.12 and ANOVA were carried out using IBM SPSS Statistics 25.

Results and Discussion

Temperature and Relative humidity distribution in the Storage Structures

The temperature profile of the storage environment is shown in Figure 5. The average daily temperature in the low energy cool barn and the ambient hovers around 24 °Cover the storage period. in the cold room on the other hand the temperatures averaged 15 °C showing a temperature differential of over 10 °C. However, the daily temperature in the cold room showed a gradual increase as the storage period following the trend observed in the ambient. The observed increase may be due to increase in the rate of respiration of the garden eggs. The daily temperature variation follows a sinusoidal curve over the storage period with the temperature in the storage structures lagging the ambient temperature. The highest average daily temperature recorded was 27.5, 26 and 21.0 °C for ambient, LECB and SCR. It should be noted that the variability observed in the temperature profiles is partly due to the frequency of opening of the doors which increases infiltration from the ambient environment. As shown in Table 1, the SCR maintained a significantly lower temperature ($p<0.05$) than the temperature maintained in the LECB and the shed (control). The temperature maintained in the LECB and the shed was however not significantly different.

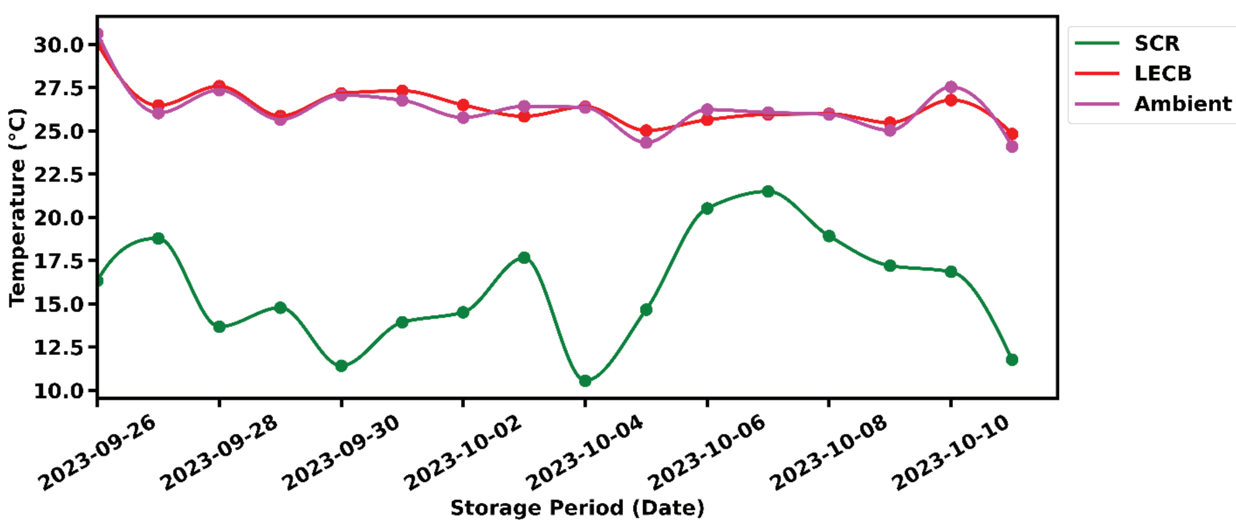

Figure 5. Temperature distribution in the storage structure and ambient

The relative humidity in the storage structures and the ambient is shown in Figure 6. The relative humidity in the low energy cool barn and solar cold room increased gradually reaching 91 and 94% respectively while the relative humidity in the ambient decreased. The average relative humidity of obtained in the LECB and SCR was above 85% which is close to the optimal storage condition for garden egg. The LECB maintained a differential of about 10 % over the ambient which suggests that evaporative cooling can take place. Although the relative humidity in the SCR and LECB are not significantly different ($p<0.05$), the moderately high temperature recorded in the LECB predisposes the stored garden egg to rot. One of the reason while high value of weight loss was recorded in the control was due to the low relative humidity which cause the stored garden eggs to lose moisture.

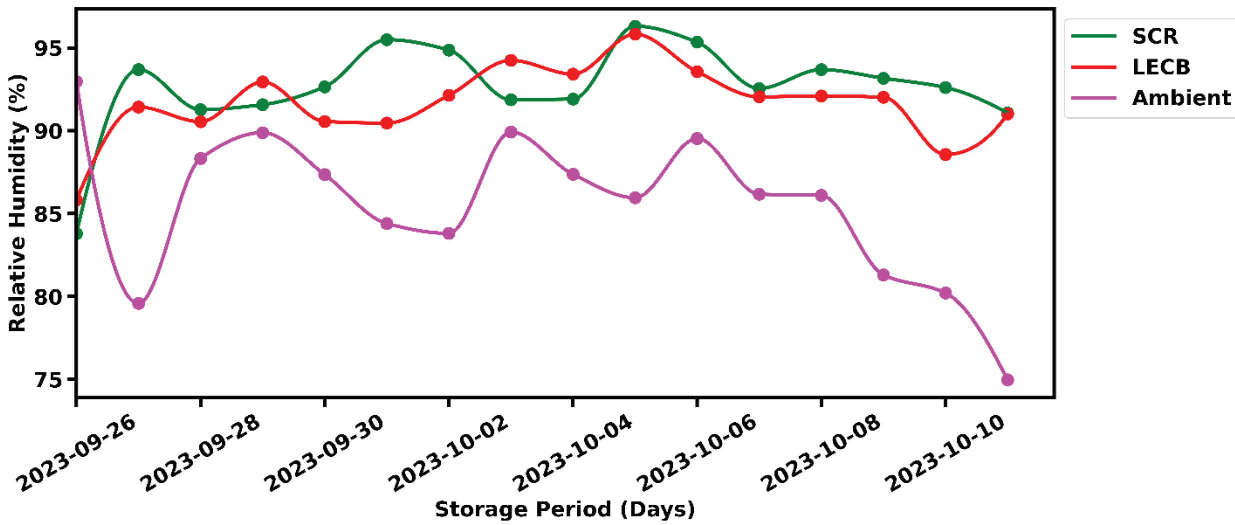

Figure 6. Relative humidity distribution in the storage structure and ambient

Table 1. Temperature and Relative humidity in the storage structures

Storage Structures	Temp	Relative humidity
SCR	15.8 ± 0.8a	92.6 ± 0.71a
LECB	26.4 ± 0.3b	91.6 ± 0.5a
CONT	26.3 ± 0.3b	85.4 ± 1.1b
Sig.	$F(2, 45) = 124.767$, $p = 0.000$	$F(2, 45) = 20.257$, $p = 0.000$

Effect of storage structure on the weight loss in stored garden eggs

The weight loss in garden eggs is shown in Figure 7. After three (3) days of storage weight loss was minimal in the storage structures including control with just about 10% lost weight. Weight loss increased as the storage period progressed with about 35% loss recorded in the control. This suggests that even though the ambient condition (temperature was below 28 C and above 75% relative humidity) causes the garden egg to lose a lot of moisture. Conversely in the weight loss at day 9 in the LECB, was still less than 30%. This suggests that the LECB will extend the shelf life of garden egg by at least 4 days. This is because the condition in the LECB has a sufficiently high relative humidity required for the preservation of fruits and vegetables although the temperature is not sufficiently low. After 15 days of storage weight loss in the SCR was just about 20%. This implies that the SCR was able to maintain the condition required for the storage of garden resulting into a shelf-life extension of about 10 days over the traditional practice of keeping fruits and vegetables under a shed. The cumulative weight loss the LECB, SCR and the ambient was significantly different ($p<0.05$) as presented in Table 2. This is expected considering the condition temperature and relative humidity recorded in the structures. Although the colour change observed in the LECB, SCR and ambient were similar, the total colour index of garden eggs stored in the SCR was significantly different from those stored in the LECB. This colour change may be associated with moderately high temperature in the LECB coupled with the high relative humidity. This result further shows that, while the SCR will be able to delay ripening which is a preservation strategy, LECB is not recommended for fruits storage with the intension of delaying ripening.

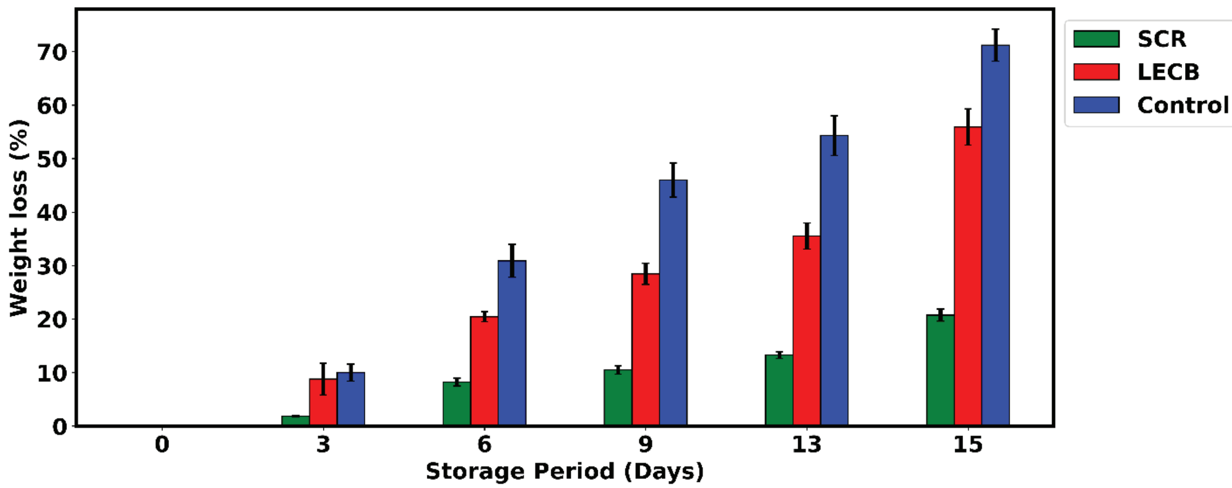

Figure 7. Weight loss in stored garden eggs

Table 2. Weight loss and colour changes in garden eggs stored in the storage structures

Storage Structures	Weight loss	Colour_change	Total Colour index
SCR	19.66 ± 1.13a	11.79 ± 1.292a	0.74 ± 0.113a
LECB	55.9 ± 3.37b	19.09 ± 2.594a	1.52 ± 0.047b
CONT	71.2 ± 3.0c	11.19 ± 2.619a	0.76 ± 0.209a
Sig.	$F (2, 20) = 156.873, p = 0.000$	$F (2, 21) = 3.330, p = 0.055$	$F (2, 21) = 5.738, p = 0.010$

Conclusion

LECB extended the shelf life of garden egg and reduce weight loss by about 40% which is a significant reduction in the GHG that would have been released into the atmosphere if the garden eggs were to be stored under the shed (traditional) practice. SCR gives a better self-life extension and a 70% weight loss. The use of the LECB which is a relatively cheap and easy to use technology will give the smallholder farmers room to keep their fruits and vegetables few days without experiencing substantial losses. The performance of the SCR showed that, solar energy should be explored for sustainable cooling in Nigeria and other west Africa subregion where energy supply from the national grid is difficult to harness. The results will help smallholder farmers and fruit marketers to adopt passive coolers and solar coolers for sustainable food loss management. Extensive tests with fruits and vegetables under varying environmental conditions is suggested for potential application of the two technologies.

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AI-Powered Renewable Energy Based Smart Crop Field Monitoring For Climate Adaptation In Nigeria

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Abstract

Climate change is a global problem, particularly for the agricultural sector, resulting in crop yield reduction, food insecurity, and economic losses. In most of Africa, existing crop monitoring systems are largely manual, fragmented, and non-scalable, failing to address climate change impacts effectively. Hence, there is an urgent need for an innovative, and sustainable energy-based climate smart agricultural system that can provide real-time data, predictive analytics, and personalized recommendations to support climate adaptation and sustainable agriculture especially in Nigeria. This paper therefore examines an AI-powered renewable energy based smart crop field monitoring system for climate adaptation in Nigeria. The system utilizes solar-powered IoT sensors to collect real-time data on precipitation, temperature, humidity, soil moisture, and crop health. This data is then transmitted to an AI-powered platform for analysis and predictive modeling, enabling farmers to make data-driven decisions on irrigation, fertilization, and pest control. The system's AI algorithm integrates machine learning and deep learning techniques to predict weather patterns, detect early signs of crop stress, and provide personalized recommendations for climate-resilient farming practices. The system includes a mobile application for farmers to access real-time data, receive alerts, and connect with agricultural experts targeting enhanced crop yields, improved resource efficiency, and promote climate adaptation. By leveraging AI and renewable energy, this system has the potential to transform the country's agricultural landscape, ensuring food security and sustainable economic growth. The proposed system's impact will be evaluated through a pilot project in selected Nigerian farms, with a focus on scalability and replicability nationwide.

Key Words: Climate change; AI-powered; Smart Agriculture; Renewable Energy; Adaptation; Real-time Data.

Introduction

Climate change is a global problem, which presents a significant challenge to the world today particularly for the agricultural sector, resulting in reduction of crop yield, food insecurity, and economic losses. Climate change is the long-term alteration of temperature and typical and less predictable weather patterns. These unexpected weather patterns can make it difficult to maintain and grow crops in regions like sub-Saharan Africa especially Nigeria that rely on farming because expected temperature and rainfall levels can no longer be relied on.

Agricultural production on the other hand, which is a foundation for the survival and development of human beings, is also impacted by rapid global climate change (Monteleone, *et.al.* 2022., Annie *et al.*, (2023); Wu *et.al.*, (2023)). Global warming not only leads to frequent extreme weather events, uneven precipitation, droughts, and floods, resulting in reduced crop yields, but also disrupts ecological balance and affects the prevention and control of crop pests and diseases (Eekhout *et.al.*, 2022; Yang *et.al.*, 2023). Moreover, climate change has caused soil degradation and scarcity of land resources, thereby impacting the sustainable development of agricultural production (Fuentes *et.al.*, 2023).

To address this challenge, strong international cooperation and innovative measures are urgently needed. Through the concerted efforts of nations, substantial reductions in greenhouse gas emissions and the promotion of sustainable technology development can be achieved. However, climate adaptation with the aim of improving farming techniques and agricultural methods with advanced technology is becoming more crucial on our fast-evolving and ecologically challenged planet, where challenges such as energy deficiency, drought, global warming, among others, have adverse effects on common agricultural practices.

Climate adaptation essentially means any measure that protects an ecosystem or community from the effects of climate change while also building long term resilience to evolving environmental conditions. Although, Many adaptation measures need to happen at the local level, so rural farming communities have a big role to play. Such measures include planting crop varieties that are more resistant to drought and practicing regenerative agriculture, improving water storage and use, managing land to reduce wildfire risks, and building stronger defence against extreme weather like floods and heat waves.

Also, in most of Africa especially Nigeria, existing crop monitoring systems are largely manual, fragmented, and non-scalable, failing to address climate change impacts effectively. Hence, there is an urgent need for an innovative, and sustainable energy-based climate smart agricultural system that can provide real-time data, predictive analytics, and personalized recommendations to support climate adaptation and sustainable agriculture.

The United Nations (UN) is promoting sustainable development goals (SDGs) that aim to create impactful agriculture industry. Artificial intelligence (AI) and Internet of things (IoT)-based smart farming technologies are transforming the agriculture industry from seedling cultivation to food processing.

Additionally, the second UN Sustainable Development Goal (SDG-2) of eradicating hunger can be accomplished with the help of the integration of AI and IoT technology in the agriculture sector. In addition to increasing agricultural output and efficiency, AI-based IoT farming can give farmers useful insights and decision-making tools that are based on current data. AI systems, for example, may assess information from sensors and other field equipment to maximize fertilization and irrigation, reducing waste and ultimately improving crop quality. Furthermore, IoT-enabled monitoring tools can help with the early detection of diseases and pests, allowing farmers to respond right away and minimize damage to their crops. Another way that AI and IoT may help SDG-2 is by promoting sustainable agriculture to minimize hunger. For instance, AI systems may instruct farmers to use electricity, water, and fertilizer efficiently, reducing their environmental effect and protecting natural resources. IoT sensors can also be used to gather data on how climate change is affecting crops and monitor the condition of the soil, allowing farmers to adapt their practices and increase crop resilience.

The Food and Agriculture Organization (FAO) of UN projects that by 2050, the world's population will further increase by 2 billion, putting more stress on agricultural land and food production (Colizzi *et al.*, 2020). AI-based IoT and machine learning technologies are being developed to improve agricultural productivity and reduce waste (Navarro *et al.*, 2020, Kakamoukas *et al.*, 2021, Mahbub, 2020).

Impact of Climate Change on Agricultural Production

As the foundation of human existence, agricultural production is particularly vulnerable to climate change, which has altered environmental factors such as temperature, precipitation, and wind speed, and affected crop growth cycles, the frequency of extreme weather events, and the occurrence patterns of pests and diseases directly or indirectly, ultimately influencing crop yield and quality.

Climate change has increased the frequency and intensity of extreme weather events (Sun et.al., 2019) potentially leading to extensive crop damage or even complete crop failure. Moreover, extreme weather events may also disrupt agricultural infrastructure, increasing the cost of agricultural production (Newman and Noy., 2023).

Carvalho, *et al.* (2020), after unscrambling data of extreme weather events and crop loss, found that agricultural production in Brazil is severely affected by extreme weather events such as droughts, hailstorms, and frosts, with droughts found to have caused a significant decrease in national agricultural production, especially in vulnerable biological communities. This study also pointed out that the losses caused by these extreme weather events have not only affected small-scale farmers and domestic and international commodity markets, but also harmed the country's economy as a result of adjusting farm subsidies and credit programs. Schmitt, *et al.* (2022) analyzed the impact of extreme weather events such as frost, heatwaves, drought, and water logging on the yields of winter wheat, winter barley, winter rapeseed, and maize in German agriculture. The study indicates that extreme weather events, particularly drought, pose significant risks to agricultural production in Germany, resulting in substantial yield losses and economic damages. Lesk, *et al.* (2022), by proposing and explaining three composite patterns of climate impact on crops and assessing historical and future trends in composite extreme events and their impact on crop yields, explored the global agricultural response to composite extreme weather events. Based on these theories and predictions, researchers have proposed new strategies aimed at limiting the risks posed by composite extreme events and climate change to crops and agriculture. Moreover, studies have found that due to the interconnection of food supply chains, the impacts of extreme weather events are also extensive and diverse, with the most severely affected sectors being fruits, vegetables, and livestock production. These impacts further extend to other non-food production sectors such as transportation services (Malik *et.al.*, 2022). Therefore, strengthening the protection and restoration of agricultural ecosystems and enhancing the adaptability and resilience of agricultural production systems have become important directions in agricultural scientific research.

Climate smart Agriculture and Renewable Energy

Doshi and Varghese (2022) proposed the concept of harnessing natural and artificial wind energy, the turbulence produced by the displacement of air due to the motion of objects such as trains. This energy harnessed can then be used in powering Internet of Things devices that enable AI-based smart farmland monitoring systems. The aim is to solve the challenges facing common agricultural practices in suburban and rural areas where vertical axis wind turbines can be set up, ultimately easing the lives of agriculturalists.

Shabab, *et al.* (2024) conducted a comprehensive review on IoT-based agriculture Management techniques for sustainable farming. The study gives a general overview of the machine abilities that smart farming is supported by, including perception, reasoning and learning, communication, task planning and execution, and systems integration. The use of robots and unmanned aerial vehicles in diverse agricultural contexts is also demonstrated in the paper, indicating the potential for improved productivity and diminished environmental effect. The report concludes by highlighting the significance of utilizing wireless communication. In (Podder *et al.,* 2021, Doshi and Patel, 2019, Singh *et al.*, 2022, Singh and Sivaram, 2022, Maraveas *et al.*, 2022, Kumar and Sharma, 2020, Lohchab *et al.,* 2018, Igri *et al.,* 2022) multiple systems are proposed for managing smart agriculture farming that monitor essential parameters, such as temperature, humidity, and soil moisture for improved efficiency and productivity. By collecting and analyzing data on these parameters, farmers can make more informed decisions about their farming practices and procedures. The proposals are based on the potential for technology to revolutionize traditional farming practices, optimize resource use, and lead to higher crop yields and better environmental outcomes. The authors' focus on essential parameters and their potential to provide a comprehensive understanding of the farming environment make their study an important contribution to the literature on smart agriculture, though further research is needed to validate their effectiveness.

Piancharoenwong and Badir (2024) explores, compares, and prioritizes the factors that influence IoT smart farming adoption, considering both the expected gains and losses. Survey data collected from 265 farmers in Thailand was analysed using structural equation modelling (SEM) to test our hypotheses. The results demonstrate that IoT smart farming is significantly influenced by both the perceived expected gains from its adoption and the perceived expected losses from climate change in the case of not adopting IoT smart farming. However, in contrast to PT, the impact of losses is not greater than that of gains. This article offers valuable insights that are essential for shaping sustainable farming practices and informing policy frameworks in the face of mounting challenges posed by climate change.

Methodology

Based on this background, this study therefore proposes an AI-powered renewable energy based smart crop field monitoring system for climate adaptation in Nigeria. Smart agriculture is one of the most promising Cyber-Physical System (CPS) applications that will positively affect human life. Smart Agriculture can preserve a significant amount of water and energy through its ability to monitor multiple resources such as irrigation and solar energy systems. As a CPS, it replaces the traditional agricultural system with a smart and modern one that provides accurate agricultural management by collecting and processing data related to the plant, the weather, and the soil, in real-time mode and using precise control methods. The system will utilizes solar-powered internet of things (IoT) sensors to collect real-time data on precipitation, temperature, humidity, soil moisture, and crop health.

The integration of energy from renewable sources into the internet of things (IoT)-based smart agricultural observation system increases its sustainability and cost-effectiveness. This data is then transmitted to an AI-powered platform for analysis and predictive modeling, enabling farmers to make data-driven decisions on irrigation, fertilization, and pest control. The system's AI algorithm integrates machine learning and deep learning techniques to predict weather patterns, detect early signs of crop stress, and provide personalized recommendations for climate-resilient farming practices. The system will include a mobile application for farmers to access real-time data, receive alerts, and connect with agricultural experts targeting enhanced crop yields, improved resource efficiency, and promote climate adaptation. In addition, using solar or wind power to power the system reduces reliance on traditional power sources, resulting in lower energy costs and lower carbon emissions.

Result and Discussion

While advancements in agricultural techniques (agronomic practices) can improve farming efficiency, these activities often require a significant amount of physical effort. Due to this demanding nature, farming is traditionally viewed as a male-dominated profession. As expected for physically intensive jobs, the findings from Table 1 reveal that the majority of respondents (90%) were male, while females comprised a smaller portion (10%). This confirms the prevalence of men in farming activities within this region. The average educational level among the farmers was 7 years. Overall, the educational background suggests there is potential for adaptation of strategies. Majority of households (74.2%) in the study area fall within the 4–6-member range. This aligns with the finding that most farmers are married and likely have children. A smaller portion (12.5%) has 1-3 members, while a minority (13.3%) has more than 6 members. This suggests that the average household size falls on 5 members, possibly due to the farmers' age being above 41 years, which might indicate established families. The study also indicate that an average farmer is 41years hence are likely within the economically active age range. The analysis of landholding size reveals that most farmers (47.5%) cultivate between 1 and 2 ha. A significant portion (44.2%) operate on plots smaller than 1 ha, while a much smaller group (8.3%) manages holdings exceeding 2 ha. This suggests that a majority of the farmers are small-scale farmers.

Table 1: Socioeconomic Characteristics of Respondents

Socioeconomic Characteristics	Frequency	Percent
Sex		
Female	24	10
Male	216	90
Level of Education		
No formal Education	10	4.2
Primary Education	112	46.7
Secondary Education	94	39.2
Tertiary Education	24	10
Mean	14	
Marital Status		
Single	18	7.5
Married	190	79.2
Divorced	24	10
Widow	4	1.7
Separated	4	1.7
Household Size		
1 – 3	30	12.5
4 – 6	178	74.2
above 6	32	13.3
Mean household size	10	
Age		
< 30	12	5
31-40	108	45
41-50	120	50

Mean	82	
Years of Experience		
1 – 5	44	18.3
6 – 10	84	35
11 – 15	48	20
16 – 20	42	17.5
Above 20	22	9.2
Mean	24	
Farm size (Ha)		
< 1	106	44.2
1 – 2	114	47.5
Above 3	20	8.3
Access to Extension Service		
No	18	7.5
Yes	222	92.5

Climate Change Awareness and Information

Table 2 shows the respondents opinion on whether they are aware of climate change or not. Majority (93.3%) of the respondents are aware of climate change. it is evident from the result that significant number of the respondents are aware of the climate change which refers to farmers understanding and consciousness about climate change. It is the foundation for actionable solutions, and it involves recognizing the causes, risks, and outcomes of climate change and global warming. The results further shows the information gathered from respondents on the access to climate information. This refers to the collection and interpretation of observations of the actual weather and climate as well as simulations of climate in both past and future periods. Majority(85.8%) of the respondents stated yes and this implies that respondents understand why global temperatures continue to rise, how the climate affects farming, and how to tackle this challenge before things get much worse. The study also examines the relationship between the intention to adopt IoT AI-Powered Renewable Energy Based Smart Crop Field Monitoring. The result revealed that 90% of the farmers are willing to adopt this innovation.

Table 2: Climate Change Awareness and Information

	Frequency	Percent
Climate Change Awareness		
No	16	6.7
Yes	224	93.3
Access to Climate Information		
No	34	14.2
Yes	206	85.8
IoT AI-Powered Renewable Energy		
No	24	10
Yes	216	90

Source: Field Survey, 2024

Distribution of respondents by Perception to Climate Change

The distribution of farmers by their perception about climate change was discussed in table below. It showed that most of the farmers indicated one factor or the other as influencing to climate change. The perception was sectioned into four (4); About the perception of the farmers about rainfall, majority (89%) of the farmers were of the opinion that climate change has caused increased rainfall as it support the disagreement of the majority (83%) that stated decreased rainfall. All farmers (100%) were of the opinion that climate change has caused late onset of rain as in support of the significant majority (50%) who stated early end of rains. Also, significant majority (65%) of the farmers stated poor distribution of rainfall. On the perception of the farmers about weather risk, the farmers (99%) agreed that flooding is seriously affecting them. All the farmers (100%) were against decreased temperature as they were in support of increased temperature (100%). Also, the table revealed that 45% and 45% of the farmers agreed and disagreed to the observation of strong wind while 10% were of no idea or information about strong wind and its implication.

Table 3: Perception of Farmers to climate Change

Rainfall Pattern	Agree (100%	Neutral (100%)	Disagree (100%)
Increased Rainfall	89.0	0.0	11.0
Decreased Rainfall	13.0	4.0	83.0
Late Onset of Rains	100.0	0.0	0.0
Early End of Rains	50.0	6.0	44.0
Poor Distribution of Rainfall	35.0	0.0	65.0
Weather Risk	Agree	Neutral	Disagree
Flooding	99.0	0.0	1.0
Decreased Temperature	0.0	0.0	100.0
Increased Temperature	100.0	0.0	0.0
Strong Winds	45.0	10.0	45.0
Climate Change Intensity	Very Intense	Intense	No Change
	97.0	3.0	0.0
Perception of Climate Change Causes	Yes	No	
Supernatural reasons	20.0	80.0	
Human Activities	75.0	25.0	
No knowledge	0.0	0.0	
Political Factors	0.0	100.0	

Climate Change Adaptation Strategies.

The section discusses the climate change adaptation strategies used by maize farmers to mitigate the effect of climate change. The results revealed that 80% of the farmers adopted agroforestry and 91% of them cultivated resistant variety (91%), use of irrigation (56%), soil fertility management (75%), weather forecast (55%). Also, about the indigenous strategies used by farmers, 67% of the were of the opinion that they shift planting dates to different crops, 45% moves to a different site, 89% involves in crop diversification, 100% adds organic manure, 80% uses mulching.

Table 4: Climate Change Adaptation Strategies

Adaptation Strategies	Percent (Yes)	Percent (No)
Agroforestry	80.0	20.0
Growing resistant variety	91.0	9.0
Use of Irrigation	56.0	44.0
Soil Fertility management	75.0	25.0
Weather forecast	55.0	45.0
Indigenous Strategies Used by Farmers		
Planting local variety	45.0	55.0
Shifting planting dates	67.0	33.0
Moving to a different site	45.0	55.0
Crop diversification	89.0	11.0
Adding organic manure	100.0	0.0
Mulching	80.0	20.0
Change to livestock management	35.0	65.0
Change timing of Farm operations	99.0	1.0
Engaging in extra income sources	100.0	0.0
Planting shade trees	56.0	44.0

Source: *field survey, 2024*

Influence of socioeconomic Characteristics on introduced climate adaptation strategies

Results on Table 6 revealed that Farmers' access to extension service and credit a increases the probability of adopting the recommended agricultural practices by 5% to curb the negative effects of climatic change, relative to not adopting any of the strategy. Access to credit of farming households enables farmers to make use of all the available information to change their management practices in response to climate change and variability. This is supported by the previous studies (Saddiq *et al.*, 2019)). As expected, the study revealed a positive relationship between access of AI-Powered renewable-based technology and climate information and the adaptation by farming households. Next, being a female-headed household decreased the probability of adopting agroforestry, cultivation of resistant varieties and irrigation by farmers.. This result is to a large extent consistent with previous study that being male-headed household positively influenced the adoption decision of climate-related strategies (Nhemachena and Hassan; 2007).

A year increase in formal education of farmers increased the farmers' likelihood of adopting the recommended agricultural practices and improved varieties strategies. Thus, more years of formal education increased the farmers' awareness of the potential benefits of adaptation to climate change. In addition, distance to farm and increase in income of farmers also increases the likelihood of adopting the recommended agricultural practices.

The indigenous climate adaptation strategies (Table 7) identified from the farming households includes: Planting local variety as against resistant varieties, shifting of planting dates, moving to a new site, crop diversification, adding organic manure, mulching, change to livestock management, change in timing of operations, engaging in extra sources of income and planting of shade trees. These set of dependent variables were tested against the same set of independent variables used for the introduced strategies.

Farmers' access to extension service, years of formal education, farm size, household size, membership of farmers association as well as marital status were found to significantly influence the use of the indigenous climate adaptation strategies. Also as expected, the study revealed a positive relationship between access of AI-Powered renewable-based technology and climate information on adaptation by farming households. Next, being a female-headed household decreased the probability of adopting agroforestry, cultivation of resistant varieties and irrigation by farmers.A year increase in formal education of farmers increased the farmers' likelihood of adopting the indigenous adaptation strategies. Thus, more years of formal education increased the farmers' awareness of the potential benefits of adaptation to climate change. In addition, distance to farm and increase in income of farmers also increases the likelihood of adopting the indigenous agricultural practices.

Table 6: Influence of socioeconomic Characteristics on introduced Climate Adaptation Strategies

	Agroforestry		Resistant Variety		Irrigation		Soil Fertility Management		Weather Forecast	
	Coef.	T-value	Coef.	T-value	Coef.	T-value	Coef.	T-value	Coef.	T-value
Age	0.0148**	2.3	0.0071	1.22	-0.0021	-0.4	0.0062	0.95	0.0087	1.26
Sex	-0.3081*	-1.85	0.3067**	2.02	0.2592*	1.87	0.0631	0.38	0.0299	0.17
Years of formal education	-0.0097	-0.81	0.0189*	1.73	0.0230**	2.31	0.0393***	3.24	-0.0156	-1.22
Farming Experience	-0.0045	-0.76	0.0021	0.39	0.0029	0.59	-0.0013	-0.21	0.0034	0.55
Marital Status	0.0304	0.26	0.0787	0.73	0.1939*	1.98	-0.1038	-0.87	0.1661	1.32
Household size	-0.0374	-1.13	0.0048	0.16	0.0520*	1.9	0.0534	1.6	-0.0454	-1.29
Farm size	0.0280	0.44	-0.0548	-0.94	-0.0505	-0.95	0.1171*	1.81	0.0169	0.25
Members of farmer association	-0.3041*	-1.83	0.3117**	2.06	0.0402	0.29	-0.6838***	-4.08	-0.5289***	-2.99
Access to extension service	0.4650**	2.44	-0.0839	-0.48	-0.1504	-0.95	0.2519	1.31	-0.0641	-0.32
Access to credit	0.1733	0.62	-0.2439	-0.96	0.1089	0.47	0.0374	0.13	0.5908*	1.99
Climate change awareness	0.1096	0.45	0.1778*	1.86	0.1591*	1.79	-0.2951	-1.2	0.2889	1.12
Access to climate information	0.1352	0.95	0.1212	0.94	0.0379	0.32	-0.0836	-0.58	0.0090	0.06
Participation in off farm activity	0.0297	0.14	-0.0060	-0.03	-0.0025	-0.01	0.1740	0.81	0.4330*	1.92
Farm Income	0.0000	0.26	0.0000	-0.9	0.0000	-0.56	0.0000***	-3.08	0.0000**	-2.28
Distance to farm	-0.0561**	-2.96	-0.0001	-0.01	0.0156	0.99	0.0408**	2.13	-0.0360*	-1.78
AI-Powered renewable energy based device	0.0258**	2.28	-0.0674	-0.8	-0.0756	-0.98	0.1019*	1.79	0.0286**	2.29
R-Square	0.4799		0.8223		0.8598		0.6596		0.5771	
F-value	5.94***		29.79***		39.48***		12.47***		8.78***	

*Source: Field survey, 2024 *,**,*** Sig at 10%, 5% and 1% respectively*

Table 7:Influence of Socioeconomic Characteristics on Indigenous Climate Adaptation Strategies

	Local Variety		Shifting planting dates		Crop rotation		Diversification		Organic manure		Mulching		Change to livestock		Change timing of operations		Engage in extra income sources		Planting Shade trees	
	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T	Coef.	T
Age	0.0037	0.67	0.0008	0.23	0.0096**	2.22	−0.0004	−0.07	−0.0010	−0.16	0.0074	1.13	0.0151**	2.15	0.0061	0.87	−0.0098	−1.6	0.0045	0.72
Sex	−0.1535	−1.09	0.0816	0.88	0.0489	0.44	−0.0302	−0.18	−0.1841	−1.13	−0.0653	−0.38	−0.0379	−0.21	0.1946	1.07	0.0512	0.32	0.0068	0.04
Years of formal education	−0.0353***	−3.48	−0.0044	−0.65	−0.0066	−0.81	0.0121	1.01	0.0267**	2.27	0.0167	1.36	−0.0097	−0.74	0.0085	0.65	0.035***	3.05	0.0258**	2.23
Farming Experience	−0.0034	−0.68	−0.0084**	−2.56	0.0035	0.87	−0.0092	−1.58	0.0084	1.44	0.0039	0.64	−0.0125*	−1.94	−0.0062	−0.96	0.0069	1.22	0.00119	0.21
Marital Status	−0.0350	−0.35	−0.0294	−0.45	−0.0199	−0.25	−0.0537	−0.46	0.2597**	2.25	−0.3051***	−2.53	0.1054	0.82	0.1503	1.17	0.0667	0.59	−0.12343	−1.08
Household size	−0.0154	−0.55	−0.0316*	−1.72	−0.0349	−1.57	0.0707**	2.17	0.0463	1.43	0.060*	1.78	−0.0701*	−1.95	−0.0014	−0.04	−0.0422	−1.34	0.0683**	2.14
Farm size	−0.1068*	−1.98	0.0221	0.62	−0.0359	−0.83	0.1367**	2.16	0.0772	1.23	0.1083	1.65	0.0126	0.18	0.0086	0.12	0.0554	0.9	0.04787	0.77
Member of farmer association	0.4179***	2.99	0.3107***	3.37	0.3225***	2.9	−0.4029**	−2.46	−0.0695	−0.43	−0.5513***	−3.25	0.0520	0.29	0.0495	0.27	0.3407**	2.15	−0.4951***	−3.09
Access to extension service	−0.0555	−0.35	−0.0612	−0.58	−0.0968	−0.76	−0.3670*	−1.95	−0.4041**	−2.17	0.0228	0.12	0.0712	0.34	0.1517	0.73	0.2027	1.11	0.16043	0.87
Access to credit	0.4451*	1.9	0.3594**	2.33	−0.0343	−0.18	0.4358	1.58	0.6001**	2.21	0.2733	0.96	0.553*	1.83	0.1235	0.41	−0.2475	−0.93	−0.08322	−0.31
Climate change awareness	0.2622	1.28	0.1549	1.15	0.1135	0.7	−0.0919	−0.38	−0.1830	−0.77	−0.1772	−0.71	−0.1593	−0.6	0.2730	1.03	0.0248	0.11	0.02724	0.12
Access to climate information	−0.0238	−0.2	−0.0814	−1.03	−0.0587	−0.62	0.0596	0.42	−0.0945	−0.68	0.0216	0.15	0.0361	0.23	0.1881	1.22	−0.1299	−0.96	0.3088**	2.25
Participation in off farm activity	0.5352***	3	0.3505***	2.98	0.5250***	3.69	0.3928*	1.88	0.2352	1.14	0.2127	0.98	0.0430	0.19	−0.3602	−1.56	0.2812	1.39	−0.3756*	−1.84
Farm Income	0.0000**	2.22	0.0000	−1.5	0.0000	−1.78	0.0000	−1.38	0.0000	−1.15	0.0000	−1.35	0.0000	−0.01	0.0000**	−2.72	0.0000	1.12	0.00000	−1.31
Distance to farm	−0.0526***	−3.29	0.0196*	1.87	0.0196	1.54	0.0240	1.28	0.0298	1.61	0.0376*	1.94	−0.0064	−0.31	0.0093	0.45	−0.0091	−0.5	0.0386**	2.11
AI-Powered renewable energy based device	−0.018	−0.24	0.026**	2.51	−0.0339	−0.54	0.137*	1.8	−0.0919	−1.01	−0.1757*	−1.85	0.0162	0.16	−0.0520	−0.51	0.2079**	2.35	−0.08890	−0.99
R-Square	0.837		0.941		0.912		0.773		0.778		0.520		0.701		0.649		0.780		0.473	
F-value	33.08***		103.77***		67.38***		21.94***		22.61***		6.98***		15.11***		11.95***		22.89***		5.792***	

*Source: Field survey, 2024 *,**,*** Sig at 10%, 5% and 1% respectively*

Conclusion and Recommendation

This study examined the influence of AI-Powered renewable energy based device on the adaptation strategies of farmers using primary data collected from 240 farming households by the administration of questionnaires. Specifically the study assessed the percentage of the smallholder farmers adopting each of the identified adaptation strategies as well as the the newly introduced AI-solar powered Algorithm using descriptive statistics and multivariate regression analysis. The study revealed that farmers adopted combination of adaptation strategies rearing from agroforestry, growing resistant varies, irrigation as well as are interested in the use of the AI powered renewable energy based device. However, Years of formal education, access to extension services, use of the AI powered renewable energy-based device, access to climate information were significant variables influencing the adoption of both indigenous and introduced climate adaptation strategies.

The study therefore recommends that farmers should be provided with improved varieties as well as irrigation materials in order to improve their yield and also ensure food security. In addition, by leveraging AI and renewable energy, this system has the potential to transform the country's agricultural landscape, ensuring food security and sustainable economic growth

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The Role of Climate-Informed Advisories in Knowledge, Attitude, and Practices Toward Climate-Smart Livestock Practices Among Pastoralists and Agro-Pastoralists in Senegal

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Abstract

Climate change poses significant challenges to livestock farming in Senegal and brings the need for climate advisories to promote adaptive strategies and enhance resilience among pastoral communities. This study investigates the improvement of the knowledge, attitudes, and practices (KAP) related to climate-smart livestock practices among pastoralists and agro-pastoralists receiving climate information through digital services in Senegal. There were 298 smallholder livestock farm households surveyed, randomly selected across 10 municipal areas of the department of Linguère in Senegal. KAP scores were generated, and Seemingly Unrelated Regression (SUR) models were employed to analyze the socio-economic factors that explain the scores.

The empirical results suggest that access to climate advisories improve livestock farmers' awareness of climate smart practices in livestock farming. The average KAP scores are 6.17 on a scale of 9; 6.56 on 12; and 4.17 on 13 for knowledge, attitude, and practices respectively. Socio-economic factors such as gender (male), number of years of livestock experience, level of education, household size, membership in an organization, and access to credit have positive effects on the KAP scores. Policymakers should consider these to improve farmers' KAP towards the use of climate advisories to develop targeted interventions. This study contributes to the growing body of knowledge on the role of digital technologies in promoting climate resilience among vulnerable agricultural communities, with a specific focus on livestock farming in Senegal.

Introduction

Livestock farming as well as the production of animal-sourced food is the major income-generating activity in Senegal's arid and semi-arid areas (Beye *et al.* 2019; DAPSA, 2021). With climate change exacerbating problems and increasing variability with already meagre water and pasture resources (Eeswaran, Nejadhashemi, Faye *et al.* 2022; Abubaker, Suleiman, Abubakar & Saleh 2021), weather and climate information services (WICS) become increasingly vital for ensuring livestock farmers' livelihoods (Houessionon, Chan, Wane *et al.* 2022). Despite this, and the noted demand for livestock WICS, the implementation of WICS in Senegal has been focused on crop production (Ouedraogo, Diouf, Ouedraogo, *et al.* 2018). With different production characteristics as compared to crops (e.g. different feed possible feed varieties, the possibility of mobility of livestock, producers being able to sell at different levels of maturity and the ability to have consistent income through the production of milk and eggs) as well as responses to disease, heat stress, water shortage as well as the sociocultural role that livestock plays in producers' livelihoods as stores of capital and insurance means that the implementation of WICS for livestock producers would differ from those of crop producers. During the late dry season, as the availability of natural pasture decreases, either supplementary feed will be used or long-distance transhumance will be conducted to areas in the south of the country where more pasture is available. Additionally, transhumance may be more necessary to access water points and ponds (Beye *et al.* 2019). Combined with increasing herd sizes and expected demand for animal-sourced foods there is increasing competition for natural resources, there are poorer quantity and quality of feeds, water scarcity, increased incidence of livestock diseases, increased heat stress and biodiversity loss (DAPSA, 2021). Therefore, the challenge is to maintain a balance between productivity, household food security, and environmental preservation. Because of this, not only does livestock WICS have to address hazards for the animals themselves, but also to plan, plant, harvest and preserve sufficient feed for the livestock during the long dry season and to encourage the adoption of climate-smart agriculture (CSA) practices (Djido, Zougmoré, Houessionon *et al.* 2021).

To address this need, the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) project in Senegal has convened a Community of Practice (CoP) that brings together stakeholders including scientists, local practitioners, in extension system, community leaders, representatives from target communities, national institutions, NGOs and livestock farmers' and actors' associations to co-produce climate-informed advisory services (Houessionon, Worou, Chan *et al.* 2023). This pilot project has been in place since June 2023, with 1243 livestock farmers receiving interactive voice response (IVR) calls every ten days as well as an estimated 24 000 agropastoralists reached through radio in the department of Louga with pastoral resource information including information on weather forecasts (daily, weekly and seasonal), onset and duration of the rainy season, evapotranspiration, temperature for maintaining the quality of milk, good hygienic practices in dairy processing, production schedules for cultivated fodder, good practices on harvesting and conservation of fodder and forage, good practices in agroforestry, information on the distribution and status of pastoral units which manage local resources (AVSF 2020), status of boreholes, monitoring water points including timing to prevent disease, market information (including feed, milk and live animal prices), as well as animal health information such as early warnings of pests and diseases, heat index, deworming and vaccination periods as well as vaccination coverage rates. CoP stakeholders ensure the timely collection and diffusion of information (Houessionon *et al.* 2023). By including a wide cross-section of actors, as well as the ability for feedback from the producers through leaving voice messages as well as using an accessible technology and produced in local languages, this pilot project seeks to overcome some of the drawbacks of a top-down approach that fail to close the gap between the disconnect between producers and scientists and in turn increase its utility for the producers (Chiputwa, Wainaina, Nakelse *et al.* 2020).

In order to measure the acceptance of climate-informed advisory amongst the participants, we surveyed 300 randomly selected smallholder farmers amongst the pilot study participants using the Knowledge, Attitudes and Practice (KAP) framework. These participants have benefited from climate-advisory services from July to December 2023. This framework has been used previously to gauge attitudes towards CSA amongst crop producers (e.g. Yegbemey, Gouwakinnou & Azumah 2024) and more generally to identify the effectiveness of strategies for behavioural change and practice setting (e.g. Saglain, Munir, Rehman *et al.* 2020; Yassin, Abu Mourad & Safi 2002).

In this paper we present the materials and methods (which includes the study area and sampling strategy as well as the data collection and model), the results (including the socio-economic characteristics of the respondents, their knowledge, attitude and practice with respect to WICS, as well as the determinants of the KAP scores) followed by a discussion of the results.

Material and methods

Conceptual frameworks

Our study followed a similar method to the one used by Yegbemey et al., 2024, which applied the knowledge, attitudes, and practices framework to a survey to investigate farmers' awareness of Climate Services in Benin. The KAP methodology investigates the relationship among knowledge, attitudes, and behaviours, where knowledge is the foundation of behaviour change, and belief and attitudes are the driving force of behaviour change (Fan *et al.*, 2018). A KAP methodology allows for an in-depth assessment and analysis of the farmers' knowledge of the problem, their feelings about it and how they currently behave or manage the issue (Schreinemachers *et al.*, 2017). As such, KAP assessments have been used to help inform educational intervention strategies to encourage behavioural change (Fan *et al.*, 2018; Schreinemachers *et al.*, 2017). Here we adopted the KAP methodology to investigate driving forces behind farmers' knowledge of and behaviours towards climate-informed advisory service for climate risks management through climate-smart practices in livestock farming.

Knowledge refers to the respondents' understanding of climate-informed advisory services. These questions aimed to identify knowledge gaps where information and education efforts could be employed (Gumucio *et al.*, 2011). Thus, we recorded the score of knowledge about weather information through binary (yes = 1 and no = 0) responses to a set of 9 questions.

Attitude refers to respondents' beliefs about climate-informed advisory with a specific focus on climate smart practices. We recorded respondents' attitudes using 12 statements as a binary variable (yes = 1 and no = 0).

Practices or behaviours are the observable actions of an individual (Gumucio *et al.*, 2011). Here respondents were asked about the use of climate-informed advisory and application of climate smart livestock farming practices. The score of practices in relation to weather information was also recorded as a binary variable (yes = 1 and no = 0) set of 13 questions.

Study area and sampling

The study was conducted in ten municipal areas across the region of Louga in Senegal: Thiagny, Yang-yang, Boulal, Dodji, Kamb, Linguere, Mboula, Ouakhakh, Sagata, Tessekere (see Fig. 1). The region of Louga is the traditional pastoral zone in the Ferlo where most pastoralists are based, and it represents the transition zone for transhumance from North to South of Senegal in the Central Groundnut Bassin, where rainfed agriculture is dominantly practiced. The pastoral zone is highly vulnerable to climate change, with a short rainy season of three months per year from July to September, and livestock farming is the main activity of the rural population of this zone. The villages were identified in consultation with representatives of livestock associations, with households being the unit of study for this study, and the heads of household as direct respondents. In case the head of household was not available, an adult who is well involved in the production activities of the household can act as respondent. A total of 298 households were randomly selected with up to 30 households per village.

Data collection

A cross-sectional study design was applied using a structured questionnaire administered individually to each respondent. The data was collected covering 298 households for the survey in December 2023 through a Computer-Assisted Personal Interviews (CAPI) system (i.e., Open Data Kit, ODK). The questionnaire was administered directly in local languages by enumerators recruited and trained on the different sections of the questionnaire. In addition to the KAP questions, data collected included socio-economic characteristics of livestock farmers including age, gender, level of education, possession of radio/phone.

Econometric model specification

Based on the assumption that the KAP items are likely to be correlated, we specified a Seemingly Unrelated Regression (SUR) model to analyze the socio-economic determinants of the scores (S) as follows:

$$S_{ij} = f(X_i) \quad \text{.......(1)}$$

With the index for the knowledge score, the attitude score, or the practice score (*j = 1, 2 and 3 respectively*). S_{ij} is the KAP score *j* of livestock farmer *i*, X_i represents the socio-economic and demographic factors linked to livestock farmer *i* and explains the different levels of indicator type score *j* of the respondent livestock farmer. We translated Eq 1 to a set of equation as follows:

$$(S_{ij} = \alpha_1 + \sum_n \beta_{1n} X_{ni} + \mu_{1i} S_{2i} = \alpha_2 + \sum_n \beta_{2n} X_{ni} + \mu_{2i} S_{3i} = \alpha_3 + \sum_n \beta_{3n} X_{ni} + \mu_{3i} \quad \text{.......(2)}$$

We defined , and as the score of KAP of climate-informed advisory services, respectively, represents the constants; stands for the coefficients of the socio-economic and demographic factors and are the random factors (errors). Equation 2 was estimated in Stata 17 software and is interpreted to analyze the factors that explain the KAP scores.

Results

Socio-economic characteristics of respondents

Table 1 shows some descriptive statistics of the socio-economic characteristics of the respondents. The farmers who were randomly sampled were 66% females with an average age of 45 years, and having on average 23 years of experience in livestock farming. Livestock farming is the main activity of the respondents. While access to credit is relatively low (26% of respondents), ownership of a radio is about 89%. We also noted that most livestock farmers, 87% exclusively rely on pasture to feed their animals. However, most of the livestock farmers do not produce fodder.

Table 1: Descriptive statistics of the socio-economic characteristics of the respondents

Variables	Mean	Std Dev
Age (years)	45.90	20.23
Gender (Yes=1/No=0)	0.34	0.23
Education (1=Yes/0=No)	0.45	0.13
Experience (years)	22.30	12.34
Access to credit (yes = 1/no = 0)	0.26	0.12
Ownership of a radio (yes = 1/no = 0)	0.89	0.32
Exclusively pasture as feed (yes = 1/no = 0)	0.87	0.17
Fodder production (yes = 1/no = 0)	0.10	0.22
Contact with extension services (yes = 1/no = 0)	0.65	0.33

Respondents' knowledge, attitude, and practice in relation to climate-informed advisory services

Table 2 presents descriptive statistics of the KAP scores. Livestock farmers had above average scores in knowledge and attitude with climate-informed advisory services while the attitude score is below the average. These results indicated that livestock farmers have positive knowledge and attitude but limited practices toward climate-informed advisory services. These results can be explained by the limited availability of climate smart practices for livestock farmers, to translate advisory into practical decision for their resilience.

Table 2: Descriptive statistics of the Knowledge, Attitude, and Practice (KAP) scores

Scores	Knowledge	Attitude	Practice
Average score	6.17 (4.60)	6.56(5.42)	4.17(3.40)

Determinants of the Knowledge, Attitude, and Practice scores

Table 3 presents the results of the regression model to analyze the drivers of the KAP scores. The regression model suggests that KAP scores are influenced by age, gender, formal education, ownership of radio by the household, experience in livestock farming, access to credit, exclusive use of pasture, fodder production and contact with extension services. We observed consistent directions of the effects of these variables regardless of the KAP scores. Age and experience have positive effects on knowledge score. Formal education and ownership of a radio have positive effects on Knowledge, Attitude, and Practice scores. Gender (male) and access to credit have positive effects on knowledge and attitude scores. The contact of livestock farmers with extension service has a positive effect on improving knowledge, attitude and practice. Feeding animal exclusively on pasture and fodder production have positive, respectively, on practice score while fodder production has positive effect on knowledge.

Table 3: Result of the Seemingly Unrelated Regression (SUR) model

Variables	Knowledge	Attitudes	Practices
Age	0.04** (.01)	0.03** (.01)	0.02** (.01)
Gender (Yes=1/No=0)	1.32*** (.34)	1.76*** (.37)	0.54** (.29)
Education (1=Yes/0=No)	2.10*** (.28)	1.54*** (.31)	0.72** (.24)
Experience	0.03 (.02)	- 0.04 (.02)	- 0.05(.01)
Access credit (yes = 1/no = 0)	0.87** (.30)	2.20*** (.32)	0.20** (.25)
Ownership of a Radio (yes = 1/no = 0)	0.13** (.29)	-0.53 (.32)	- 0.65(.25)
Exclusively pasture as feed (yes = 1/no = 0)	0.54 (.54)	0.30 (.59)	1.05** (.46)
Fodder production (yes = 1/no = 0)	.89** (.37)	.14 (.40)	.51* (.31)
Contact with extension services (yes = 1/no = 0)	0.74** (.39)	0.61** (.42)	1.68*** (.33)
Constant	4.37*** (.90)	6.32*** (.97)	5.03*** (.77)
RMSE	2.76	2.98	2.35
R square	0.56	0.52	0.64
Prob	***	***	***

** Significance at the 10% level; **significance at the 5% level; ***significance at the 1% level*

Conclusions and policy implication

Climate-informed advisories significantly enhance the knowledge, attitudes, and practices (KAP) toward climate-smart livestock practices among Senegal's pastoralists and agro-pastoralists. The study found that socio-economic factors such as gender, education, experience, credit access, and extension services positively influence KAP scores. Policymakers should prioritize these factors to improve the effectiveness of climate advisories. Targeted interventions, such as gender-inclusive programs, educational initiatives, and increased access to credit and extension services, are essential to bolster climate resilience in livestock farming. This approach will ensure sustainable livestock management and improved livelihoods in the face of climate change.

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Parallel Session 3

Theme: Youth Engagement, Women Empowerment, and Agribusiness Development for CSA

Gender Differentials and Distributional Effect of Climate-Smart Agriculture Practices on Farm Production and Welfare: Evidence from Nigeria

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Abstract

Climate change impacts men and women differently due to differences in their traditional roles, societal expectations, and livelihoods. Climate-smart agriculture (CSA) has the potential to mitigate the adverse effects of climate change and directly influence the well-being of households. However, the adoption of CSA practices at the farm level in developing nations is still low. This study investigates gender differences in adoption of climate-smart agricultural practices and its distributional impact on farm production and household welfare in Nigeria. We used a cross-sectional sex-disaggregated survey data collected from a random sample of 624 farm households, 138 male and 122 female of which are CSA practices adopters and the rest are non-adopters. We measure impact of adoption on three outcome variables: total farm yields, per capita household income, and per capital food consumption expenditure. The novelty in this study is the use of a conditional instrumental variable quantile treatment effects to control for selection bias that may arise from both observed and unobserved factors. Findings show that adoption significantly impacts the farm productivity and welfare outcomes across gender. Significant gender gap exists in farm productivity and welfare outcomes as male farm households fare better compare to their female counterparts. Farm household decision to adopt CSA practices is influenced by education, farm size, awareness of CSA, access to extension and credit, and membership of association across gender. Also, the impact of adoption is higher at the lower end of the distributions of farm and welfare outcomes in male and female households. This finding highlights the significance CSA adoption in improving farm yield and farmers' well-being. Policies that are aimed at bridging gender gap in CSA practices adoption among farming households may actually have significantly higher impact in narrowing gender gap in farm yield and household welfare.

Keywords: Adoption; climate change; climate-smart agricultural practices; distributional impact; gender; quantile regression; farm household, welfare

Introduction

Globally, the consequences of climate change on agricultural productivity are significant. Farmers face numerous challenges as a result of rising temperatures, altered precipitation patterns, a rise in the frequency of extreme weather events like floods and droughts, and changes in the patterns of pests and diseases. Due to its high greenhouse gas emissions (GHG), agriculture is both the most sensitive sector to the consequences of climate change and a major contributor to the problem. For example, according to Stetter and Sauer (2022) agriculture accounts for 14% of global greenhouse gas (GHG) emissions. As a result of the clean energy transition, this percentage will probably increase dramatically as emissions from other sectors decrease (World Bank, 2021). However, agriculture is particularly vulnerable to the effects of climate change (Habtemariam *et al.* 2020). As to Zhao *et al.* (2017), a rise of one degree Celsius in the mean temperature will result in a 6.0% reduction in wheat production, 3.2% in rice production, 7.4% in maize production, and 3.1% in soybean production. Since agriculture employs more than half of the labour force in the Africa sub-Saharan region, it is essential to the reduction of poverty (OECD, 2016; Mkpado and Mkpado, 2020). The areas most affected by climate change are those where rain-fed agriculture provides the majority of the population's income (McCullough, 2017; Giller *et al.,* 2021). Therefore, a decline in agricultural output causes most households' income to drop significantly or completely. Lower agricultural output as a result of climate change adaptation reduces food security and stunts economic growth (Abd-El-mabod *et al.*, 2020; Jawid, 2020). The farming community can lessen the effects of climate change on agriculture by implementing climate-smart agricultural practices (CSA) (Shahbaz *et al.*, 2021).

The goal of climate-smart agriculture (CSA) is to move agri-food systems toward environmentally friendly and climate-resilient methods. It encompasses investments, institutions, policies, technology, and actions that take place on and off the farm (Wakweya, 2023). It seeks to increase agricultural productivity and build the resilience of smallholder farmers at the same time (Lipper *et al.,* 2014). The Food and Agriculture Organization of the United Nations (FAO) introduced the Climate-Smart Agriculture (CSA) idea in 2010 during the Hague Conference on Agriculture, Food Security, and Climate Change. Farmers must implement and spread CSA techniques in the context of climate change and variability. CSA is a customized adaptation of one or more techniques to local production conditions rather than a practice that is implemented globally. The adoption of CSA practices at the farm level in developing nations is still low, despite significant efforts and investments to improve CSA. Adoption of a wide range of CSA practices is typically hampered by the need for upfront investments in permanent inputs like equipment and short-term investments in inputs like fertilizers and seeds. (Gikonyo *et al.,* 2022; Teklu *et al.,* 2023). Gender differences in access to and use of climate technology intensify the impact of climate change on food production in Sub-Saharan Africa (SSA) and endanger the livelihood of millions of people, particularly women. Since women make up the majority of the disadvantaged and vulnerable groups in the region, they are more susceptible than men to the detrimental effects of climate change (Duffy *et al.*, 2021; Phiri *et al.*, 2022). They do not have the same rights to own and access land as men have. Their reliance on small-scale agriculture is comparatively higher, and it is adversely affected by climate change. In Sub-Saharan Africa (SSA), gender equality and risk management related to climate change are essential for sustainable development. To improve farm households' resilience and capacity for adaptation, it is crucial that they adopt a range of Climate-smart Agriculture (CSA) techniques at the farm level. To reduce climate impacts, CSA practices must be used. Researchers must comprehend the role that gender plays in the adoption of CSA practices on farms, as CSA adoption at the farm is not gender neutral (Twyman *et al.,* 2014). There is a wealth of literature available regarding CSA adoption at the farm level. However, the adoption of CSA methods at the farm level in relation to gender and the inventiveness of women farmers is still the subject of relatively few studies.

It is crucial to include women in the implementation of climate-smart agriculture. Studies like Ahmed *et al.* (2016) suggested that knowledge of unequal power relations and levels of resource availability is necessary to understand gender-differentiated susceptibility, risk exposure, coping capacity, and women's ability to recover from climate shocks. Antwi-Agyei *et al.* (2017) discovered, for instance, that gender roles can affect both the adoption of adaptation practices and sensitivity to climatic variability. Remteng *et al.* (2021) also pointed out that tackling gender issues could benefit sustainable development, especially in the areas of agricultural and water resource management, as well as climate mitigation and adaptation. While numerous studies have outlined significant climate-smart measures and looked at barriers to their adoption at the farm level, it's equally critical to take into account who in the family is implementing and reaping the benefits of these activities. Both men and women must adapt in order to make agricultural households more resilient and to make sure that the needs and preferences of both sexes are satisfied, especially in light of the different roles that men and women play in the economy. Men and women experience climate shocks and stressors differently, have varying capacities to respond to climate change, and have different preferences for how they respond to its impacts, according to the growing body of research on gender and climate change (Huyer 2016; Jost *et al.* 2016; Bryan *et al.* 2017; Kristjanson *et al.* 2017). Many factors, such as gender disparities in how people perceive and are exposed to climate change, access to resources and information for adaptation, decision-making authority limitations, and social norms that restrict women's options, can be attributed to the gender gap in the adoption of climate-smart practices (Bryan *et al.* 2017, Jost *et al.*, 2016). Additionally, current research indicates that reducing the gender gap in agriculture would have a significant impact on the sector, leading to improvements in productivity efficiency (Seymour 2017). Furthermore, according to De Pinto *et al.* (2019), involving women in agricultural decision-making might hasten the adoption of climate-smart measures like increasing crop diversification. A growing corpus of studies has investigated how CSA practices affect the three core components of climate-smart agriculture (CSA) systems: production, adaptation, and mitigation (Lopez-Ridaura *et al.* 2018; Branca *et al.* 2021; Sedebo *et al.* 2022). But just one aspect of the CSA system's implications—household income, agricultural outputs, and carbon emissions—is taken into account by the majority of these research (Amadu *et al.* 2020; Bazzana *et al.* 2022; Israel *et al.* 2020). Amadu *et al.* (2020), for instance, discovered that the maize production of participants in the Agriculture for Life Advancement project in southern Malawi who adopted CSA techniques was 53% greater than that of non-adopters. Despite the encouraging findings of the current research, there are still significant gaps in the field.

Prior research has presumed that the adoption intensity of CSA methods has a uniform effect on household welfare and agricultural productivity. Adoption of CSA practices, however, can have differing effects on rural households at the upper and lower levels of the agricultural productivity and welfare outcomes distribution. This is not unexpected given that farmers are bestowed with distinct resource endowments (land and machinery) and socioeconomic characteristics (e.g., age, education, and innate ability). To the best of our knowledge, however, the potentially heterogenous impacts of CSA practices adoption on farm output and welfare from a gender viewpoint have not been investigated. In order to capture household welfare, we also take into account a number of outcome variables in this study, such as total farm sales, farm yield, and per capita food consumption expenditure. The majority of research exclusively looks at particular indicators related to household economics, like crop income and per capita consumption expenditure (Fentie and Beyene 2019; Sardar *et al.* 2021). A thorough knowledge of the consequences of adopting CSA practices can be obtained by measuring household welfare from a different of angles. Due of women's heightened susceptibility to shocks associated to climate change, a large portion of the study conducted to date on the relationship between gender and climate has focused on the detrimental effects on them. Furthermore, little is known about how gender influences the ownership, management, and control of intra-household resources—all crucial elements in altering the gender-based adoption pattern of CSA activities. So, the purpose of this work is to close this knowledge gap. Therefore, this study fills this vacuum by giving empirical data and provides a first attempt to research the distributional impact of the CSA practices adoption on farm production and household welfare in Nigeria by gender using quantitative evidence from a cross-sectional dataset of rural farming households. The following are the immediate policy issues addressed in this study (1) What factors influence farming household' decision to adopt CSA practices by gender? (2) Is adoption of CSA practices enhanced farm productivity and household welfare outcomes based on gender? Answering these questions is central to the understanding the effects of CSA practices adoption at different points of the farm productivity and welfare distribution would provide a more detailed insight into the economic impacts of CSA adoption.

Our contributions to the literature on CSA practices adoption include first, we use sex-disaggregated data from a cross-section of farming households to evaluate gender disparities in the adoption of CSA techniques and their influence on farm productivity and welfare outcomes. While the majority of research on CSA conducted globally has exclusively examined farms run by men, our study aims to close the gender gap in research on CSA adoption on farms. Second, in accordance with Xiance *et al.* (2024), we assessed household welfare using a number of outcome variables, including total farm yields, per capita household income, and per capital food consumption expenditure. This approach offers a thorough grasp of how adoption of CSA techniques affects the welfare of agricultural households. Thirdly, we use the quantile regression technique developed by Koenker and Bassett (1978) to evaluate the effects of adopting CSA practices at various levels in the welfare distribution, in accordance with Awotide *et al.* (2022). Nevertheless, the coefficient estimates using conventional quantile regression methods could be biased in the event of endogeneity or self-selection issues (Melly, 2006; Wehby *et al.*, 2009; Chernozhukov and Hansen, 2004). Thus, using the instrumental variable quantile regression (IVQR) developed by Chernozhukov and Hansen (2005) and Chernozhukov and Hansen (2008) to identify the quantile treatment effect, we isolate the causal impact of adoption along the distributions of the outcome variables while controlling for selection bias that arises from both observable and unobservable sources of heterogeneity, resulting in more robust estimates.

The rest of the paper is organized as follows: a review of relevant literature on CSA adoption is presented in Section 2, followed by a description of the study area, data, and sampling methods, and empirical strategy in Section 3. Results and discussion are reported in Section 4. Finally, the concluding remarks are presented in Section 5.

Review of literature

Climate change impacts men and women differently due to differences in their traditional roles, societal expectations, and livelihoods. Because susceptibility is frequently influenced by socioeconomic conditions, livelihoods, people's capability, and access to knowledge, information, services, and support—all of which may vary depending on a person's gender—the effects of climate change and related adaptive tactics are not gender-neutral. Men and women may also employ distinct coping mechanisms. Case studies demonstrate that increasing women's workloads and decreasing impoverished households' assets are two significant consequences of environmental stress in farming systems (Jost *et al.*, 2015; Agwu and Okhimamwe, 2009; Goh, 2012). In the meantime, both sexes are adopting new farming techniques that should increase their resistance to the consequences of climate change (World Bank, FAO, and IFAD, 2015). Farmers must improve or alter their agricultural systems by implementing new procedures, practices, and organizational frameworks in order to lessen the effects of climate change on agriculture. Using climate-smart farming techniques is one approach to do this (Shackleton *et al.*, 2015; Rippke *et al.*, 2016). An integrated strategy to managing agriculture, known as "climate-smart agriculture" (CSA), attempts to reduce greenhouse gas emissions, improve greenhouse-change resistance, and increase agricultural output and incomes in a sustainable manner (FAO, 2013). Conservation agriculture, cover crops, integrated crop-livestock management, improved nutrient management, improved water management, and other long-standing techniques are some of the methods that are combined into CSA (Aggarwal *et al.*, 2013; Aryal *et al.*, 2018). The adoption of climate-smart agricultural practices (CSA practices) in sub-Saharan Africa has garnered increasing attention, as seen by the works of Alemaw and Simalenga (2015), Tesfaye *et al.* (2017), and Notenbaert *et al.* (2017).

Many studies have been conducted on the impact of gender inequality in agriculture on the uptake of sustainable farming methods in developing nations. Similarly, gender barriers influence the degree to which various CSA techniques are adopted in SSA. This topic deserves in-depth consideration since, among other ways that climate change exacerbates the gender gap in agriculture, it leads to men migrating in search of employment while women take on more agricultural duties (Gondwe *et al.*, 2022). Furthermore, the adoption of new agricultural methods in Sub-Saharan Africa (SSA) may necessitate alterations to deeply ingrained cultural and social norms, as many agricultural practices are intricately linked to the local surroundings. For instance, if these traditions are connected to specific gender roles in agriculture and the new practices go against these expectations, they can encounter opposition (Makate, 2020; Kinyili and Ndunda, 2022). Women's ability to embrace CSA techniques is frequently limited by societal and cultural constraints. According to earlier research, women are frequently prevented from engaging in agroforestry in various SSA communities because it is seen as culturally improper for them (Kiptot & Franzel, 2012). Research has also shown how crucial it is to question some of the gender norms in SSA if doing so improves gender relations and encourages women to participate in or embrace CSA behaviours (Wekesah *et al.*, 2019).

Empirical data indicates that CSA behaviours are adopted in SSA in a gender-related manner. For instance, CSA practices are more frequently used on plots maintained by men than by women in Ethiopia and Nigeria (Teklewold, 2023). On the other hand, in Malawi, plots overseen by women are more likely to implement CSA practices (Teklewold, 2023). Furthermore, different nations adopt CSA techniques in different ways depending on the gender of the adopter. In Ethiopia and Nigeria, for instance, there is a higher uptake of CSA techniques on plots overseen solely by males or in conjunction with women. Tanzania and Malawi, however, exhibit the reverse situation (Teklewold, 2023). According to research, women are more likely than men to embrace CSA methods connected to crops, whilst men are more likely to accept practices related to livestock and agroforestry (Ngigi *et al.*, 2017; Nchanji *et al.*, 2022). Disparities in the preferred information source and gender access to information have also been reported. For instance, in Kenya, women prefer to get their information from social groups and radio, whereas males prefer to get their information from print media, television, extension officers, and local leaders (Ngigi *et al.*, 2017; Ngigi and Muange, 2022). These seem like odd preferences. Furthermore, women who reside in families led by men also have less access to extension services than do men (Tsige *et al.*, 2020). Women's ability to get familiar with and implement new CSA practices may be hampered by their limited access to extension services in comparison to males. Furthermore, according to Jones *et al.* (2023), some CSA practices are more likely to be embraced by landowner farmers, which may provide a challenge for female farmers who lack land ownership rights or who are landless. Understanding the many ways that various socioeconomic groups are impacted by and responding to climatic changes is essential to addressing gender disparities in the context of adaptation and resilience. Then, it is crucial that knowledge be made available and accessible to men and women, boys and girls, and that any possible increase in workload be reduced when resilience-enhancing techniques and approaches are developed. Notably, gender-related time poverty is another factor that could influence the uptake of CSA practices. In Mozambique, for instance, women must devote a notably greater amount of time to taking care of home requirements even though the agricultural economy is mostly dependent on cooperative labour and both sexes invest comparable amounts of time in crop cultivation (Arora and Rada, 2020). Women are frequently at a disadvantage when it comes to the adoption of CSA technologies and practices, as gender is linked to differences in roles and responsibilities, access to resources that influence adoption decision-making processes, knowledge, norms, and decision-making power (Murray *et al.*, 2016; Bryan *et al.*, 2017). Research on the relationship between gender and CSA emphasize how crucial it is to understand the various obstacles that men and women encounter when it comes to their needs, preferences, and ability to adapt to climate change. In order to advance gender parity in agriculture and strengthen SSA's agricultural systems' ability to withstand the effects of climate change, these issues must be addressed.

Methodology

Study Area: This study was carried out in the North central region of Nigeria. This region was selected for this study due to its large number of farming households and is regarded as food basket of the country. The region is geographically situated in the middle belt of the country, scaling from the west, around the confluence of the Rivers Niger and Benue. It is composed of six states: Benue, Kwara, Niger, Plateau, Nasarawa, Kogi, and Abuja, the Federal Capital Territory. It is located on the latitude 7^0 and 10^0N and longitude 3^0 and 14^0E covering about, 730,000 km^2. In addition to having some of Nigeria's most intriguing architecture, the area is rich in natural geographical features. There are also a lot of historical and colonial artifacts in the area. North Central Nigeria is home to more than 24 million people (National Bureau of Statistic, 2020). The Guinea Savannah Zone, which makes up 90% of the land area, is the primary source of vegetation in the area, and its climate is partially influenced by that of Nigeria's northern and southern regions. Most of north central Nigeria experiences the wet and dry conditions of the tropical savannah climate. The length of the rainy season decreases proportionately with northward movement. In general, the area has high temperatures. Rice, beans, cassava, sweet potatoes, maize, soybeans, sorghum, millet, sesame, and cocoyam are only a some of its abundant agricultural crops.

Data Collection and Sampling Techniques: This study was conducted between November 2023 to February 2024. We used sex-disaggregated data from a cross-section of rural farming household through a multi-stage stratified random sampling approach. At the first stage, we randomly select 50% of the states in the region (Benue, Kwara, and Nasarawa). In the second stage, there are 52 local government areas (LGAs) in the 3 selected states (Benue 23; Kwara 16; Nasarawa 13), we randomly select 25% of the LGAs (Benue 6, Kwara 4, and Nasarawa 3) making a total of 13 LGAs. We then retrieved the list of farming household from the Department of Agriculture of each selected LGA. At third stage; we randomly select 4 farming communities from each of the sampled LGAs and totaled 52 farming communities used for the study. In the final stage; we randomly select 12 farming households (6 male and 6 female) from each of the selected farming communities, resulting in a total of 624 respondents for the study. Hence, out of the sampled farming households, 5 adopters of CSA practices and 7 non-adopters were therefore sampled from each farming community, making 260 adopters and 364 non-adopters of CSA practices. We try to sample equal number of male and female household but however, ended up sampled 138 and 122 adopters, 197 and 167 non-adopters among male and female respondents respectively, for the study. In addition, most of the farming communities selected are homogenous in terms of socio-demographic and agroecological zone and have agriculture as their primary occupation.

Our study adopted structured questionnaire deployed on an Android electronic tablet software (kobocollect) and administered to farming household to gather primary data. We employed the services of trained enumerators and agricultural extension agents for the survey. The survey instrument structured to help achieve the study objectives. We collect data on farm households' socioeconomic characteristics, crop production, types of crops grown, access to varietal information, credit and extension services, expenditure on food and other items, income from farm sales, other means of livelihoods, off-farm engagement, asset ownership, access to output markets, and membership of farmers' associations, and household decision to adopt CSA practices among others. The description of some of the variables included in the model are presented in Table 1. In this study, we employed three important welfare outcomes such as total farm yields, per capita household income, and per capital food consumption expenditure. The total farm yield represents the crop yield per production and was measured in kilogram/hectare (kg/ha). Following recent impact studies, Olagunju *et al.* (2019), Abdoulaye *et al.* (2018), Wossen *et al.* (2017), Wossen *et al.* (2018) and Ogunniyi *et al.* (2017), have used yield as a reliable measure of productivity. The per capita household income was measured as total household income in Nigeria naira (₦) divide by total number of household members while per capita food consumption expenditure was measured by asking the sample households on food expenditure in Nigeria naira (₦) for the preceding year covering 12 months consistent with the World Bank's LSMSISA standard module. The treatment variable is the adoption of CSA practices among farming households and it is measured as dummy variable which takes a value of 1 if a farming household adopt any of CSA practices, and 0 otherwise.

Table 1: Definitions of variables used in the model

Variable	Definition
Outcome variables	
Total farm/crop yield	Total farm output/crop yield per hectare of land cultivated (kg/ha)
Per capita household income	Total household income ('000 (₦/capita) divided by the total number of household members
Per capita food consumption expenditure	Total expenditures spent on food in Nigeria naira (₦) divided by the total number of household members
Treatment variable	
Adoption of CSA practices	1 if household adopt any of CSA practices; 0 otherwise
Control variables	
Age	Age of household head (years)
Marital status	1 if household head is married: 0 otherwise
Education	Number of years of formal education
Household size	Number of family members in the household
Ownership of farmland	1 if the farmer-owned land, 0 otherwise
Total farm size	Total farm size cultivated in hectare (ha)
Farming experience	Number of years of farming experience (years)
Membership of farmers' union	1 if the farmer is a member of any farmers organization; 0 otherwise
Extension service	1 if the farmer has access to extension service; 0 otherwise
Access to credit	1 if the farmers have access to credit service; 0 otherwise
Awareness of CSA practices	1 if the farmer is aware of any CSA practices; 0 otherwise
Access to climatic information	1 if the farmer has access to climate information; 0 otherwise
Access to agricultural training	1 if attended any agricultural training; 0 otherwise
Distance to nearest market	Distance of farmer to the nearest market (km)

Source: Field survey (2023)

Estimation strategies

Farm household's decision to adopt CSA practices can be considered under utility maximization framework. Following Foster and Rosenzweig (2010), the adoption usage of agricultural innovation and inputs use are the outcomes of optimization by heterogeneous agents. Thus, optimization occur in the presence of emerging constraints on the farm households' decision making based on budget, information and access to credit, and on the availability of both the innovation and other inputs. Therefore, farm households' decision to adopt CSA practices may be viewed through the lens of constrained optimization where the farm household chooses the technology if it is available, and affordable, and its usage is expected to be beneficial (De Janvry *et al.,* 2010). For instance, a rational farm household would choose to adopt CSA practices if the expected utility from this adoption (P_1) is greater than that from non-adoption (P_0). This utility gain from adopting CSA practices

($P_* = P_1 - P_0$) can be expressed as a function of an observable vector of covariates (Z) in a latent model as follows:

$$P_i^* = \alpha Z_i + \mu_i, with\ P_i = \begin{cases} 1\ if\ P_i^* > 0 \\ 0\ otherwise \end{cases} \dots\dots\dots\dots\dots\dots\dots\dots..(1)$$

where is a binary variable that equals 1 if a farm household i adopt any CSA practices and zero otherwise; P_i is a vector of parameters to be estimated and is a vector of household demographics, socio-economic, and farm-level characteristics; and is a random error term assumed to be normally distributed. Adoption of CSA practices among farming households is expected to impact various outcome variables at the farm or household level. Following normal distribution function, the model to estimate the probability of observing a farmer using CSA practices can be expressed as:

$$Q(P_i = 1|Z) = \varphi(Z'\gamma) = \int_{-\infty}^{Z'\gamma} \frac{1}{\sqrt{2\pi}} exp\left(-x^2/_2\right) dx \dots\dots\dots\dots(2)$$

where Q is the probability that the ith farm household will adopt any of the CSA practices, and 0 otherwise. Since the estimates of the probit model provide only the direction of effects, the marginal effects are usually estimated to interpret the actual change in the probability of covariates included in the model:

$$Marginal\ effect = \gamma_i \varphi(x) \dots\dots\dots\dots\dots\dots....(3)$$

where γ_i = coefficient of the variables; f(x) = the cumulative normal distribution value associated with the mean dependent variable from the probit estimation. However, evaluation of the impact of adoption of CSA practices on the distribution of farm productivity and welfare outcomes required the estimation of the conditional linear quantile model as follows:

$$R_i^\tau = Z_i \propto^\tau + P_i \beta^\tau + \mu_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots(4)$$

where β^τ represents the quantile treatment effect (QTE) of adoption of CSA practices (). corresponds to the th quantile of the distribution of the welfare outcomes. is a vector of observed covariates included in the model (demographics, socio-economic, and farm-level characteristics); is a vector of parameters of the covariates to be estimated; is the unobserved random variable. However, the treatment (adoption of CSA practices) is not-random i.e., farm household self-determine whether to adopt or not and this process of self-selection may render CSA adoption endogenous, thus, this endogeneity should be addressed to produce coherent estimations of the consequences linked to CSA practices adoption on outcome variables. Hence, Equation (4) may give wrong impact evaluation.

Following recent distributional impact studies such as Awotide *et al.* (2022), Olagunju *et al.* (2019), Chernozhukov and Hansen (2008), Okumu and Muchapondwa (2020), and Abadie *et al.* (2002) we estimate the distributional impact of adoption of CSA practices on the farm productivity and welfare outcomes, using the QTE conditional on covariates, as originally developed by Abadie *et al.* (2002). To estimate the distributional impact of adoption, we employ the conditional IV-QTEs approach developed by Abadie *et al.* (2002). An appropriate binary instrumental variable is a prerequisite for this model to generate consistent estimates. Hence, an appropriate instrument must be correlated with the farm household's decision to adopt and uncorrelated with farm productivity and welfare outcomes. Finding an appropriate instrument is not a trivial issue. Recent study by Awotide *et al.* (2022), have argued that awareness about the capabilities of CSA technologies to mitigate the impact of climate change among the potential adopters is a good instrument for its adoption. Therefore, we employ awareness of CSA practices as an instrument for the adoption of CSA practices. It is reasonable to say that farmers' level of awareness about the capabilities of CSA practices to mitigate climate change effects will motivate farmers to adopt CSA practices but will not directly affect their outcome variables. Based on the assumption of the inclusion of an appropriate binary instrument, the empirical specification of the Abadie *et al.* (2002) conditional IV-QTEs model is specified as follows:

$$\beta(\hat{\tau}_{IV}, \hat{\delta}\tau_{IV}) = argmin \sum W_i^{AAI} . \rho\tau(S_i - Z\beta_i - P_i\delta) \dots\dots\dots\dots\dots\dots\dots (5)$$

where:

$$W_i^{AAI} = 1 - \frac{P_i(1-V_i)}{1-pr(V=1|Z_i)} - \frac{(1-P_i)V_i}{pr(V=1|Z_i)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

where is the instrumental variable (awareness of CSA practices). The causal effect estimated is the local QTE among the compliers, that is, the group of farm households who are aware of CSA practices and have adopted CSA practices. By construction, the weights in equation (5) are not necessarily positive, and the minimand is not necessarily convex. Abadie *et al.* (2002) acknowledge this problem and suggested an alternative positive weight , that can be estimated using a non-parametric local linear regression. Following Frölich and Melly (2010), the probability of being aware of CSA practices is needed to compute the weight is estimated using a local logit non-parametric estimator. This estimation was done using ivqte command in STATA (Frölich & Melly, 2010).

Results and Discussion

Summary of descriptive statistics: Table 2 provides an overview of the statistical details for all variables examined in the study, accompanied by a comparative examination centered on the adoption of climate-smart agricultural (CSA) practices by farming households. In this investigation, we consider the adoption of CSA practices as our treatment variable of interest, recognizing its significant impact on enhancing both farm productivity and household welfare within the community. This variable was assessed as binary, with a value of 1 indicating adoption by the head of the farming household, and 0 representing non-adoption. Our analysis uncovers a noteworthy contrast in the adoption of CSA practices among farming households based on gender within the research area. Drawing from Abdoulaye et al.'s (2019) recent study, which focused on welfare outcomes, we opted to utilize per capita household income and per capita food consumption expenditure as our indicators of interest. Unlike commonly used binary indicators, which may not facilitate distributional impact analyses effectively, these continuous variables better align with the objectives of our study. Table 2 illustrates that the average farm/crop yield stands at 4,372.49 kg/ha for male farming households and 3,088.96 kg/ha for female farming households. However, among male households that adopted CSA practices, the mean farm/crop yield significantly rises to 5,370.39 kg/ha, in contrast to the counterfactual non-adopters, with 3,553.05 kg/ha, at the 1% significance level. Similarly, among female households embracing CSA practices, the mean farm yield per hectare reaches 3,989.37 kg/ha, compared to 2,314.63 kg/ha for non-adopters, also significant at the 1% level. Nonetheless, a significance difference exists in the farm/crop yield between CSA adopters of male and female farming households, which may be attributed to factors included in the empirical model. The Kernel density graphs depicted in Figures 1 and 2 illustrate that, at the lower end of the distribution of farm/crop yield, farming households adopting CSA practices tend to achieve higher yields compared to their non-adopter counterparts across genders. This outcome could be attributed to the varied effects of adoption on other input factors utilized by resource-constrained farming households. However, as the distribution shifts towards the upper end, the yield of CSA adopters surpasses that of non-adopters. This underscores the necessity of conducting a distributional impact assessment of CSA practices adoption. Other outcome variables include per capita household income and food consumption expenditure. Table 2 indicates that per capita household income and food consumption expenditure are significantly higher among adopters of CSA practices compared to non-adopters in male farming household sub-samples, with values of NGN25,732.52 and NGN2,871.52 respectively. In female farming households, adopters of CSA practices similarly exhibit higher per capita household income and food consumption expenditure, with values of NGN24,597.31 and NGN24,597.31 respectively, compared to their non-adopter counterparts. The disparity between male and female farming households concerning per capita household income and food consumption expenditure amounts to NGN1,135.21 and NGN1,049.33 respectively.

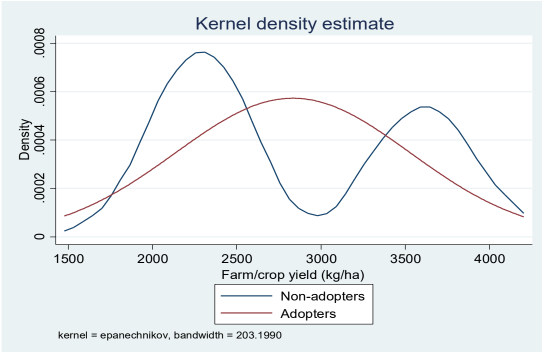

Figure 1: Kernel density estimate of the log of total farm/crop yield (kg/ha) of adopters and non-adopters of CSA practices among male farming households

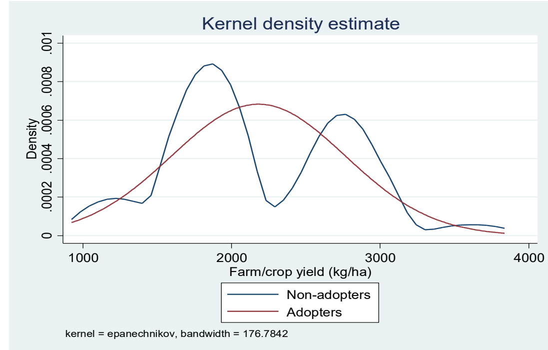

Figure 2: Kernel density estimate of the log of total farm/crop yield (kg/ha) of adopters and non-adopters of CSA practices among female farming households

Apart from the outcome variables outlined in Table 2, we incorporated additional factors believed to influence the uptake of CSA practices among both male and female heads of farming households. These factors, known as covariates, encompass a range of demographics and socioeconomic characteristics, including age, marital status, education level, household size, land ownership, farm size, farming experience, association membership, access to extension services and credit, awareness of CSA practices, access to climate information, agricultural training, and distance to nearest markets. The analysis reveals significant variations in most of these covariates between adopters and non-adopters of CSA practices among male and female farming household heads. Generally, CSA adopters tend to be older, married, better educated, with larger households and farms, and possess more farming experience across both genders. They also demonstrate greater access to institutional support, including extension services, credit facilities, awareness programs, and agricultural training compared to non-adopters. For instance, among male farming households, the average household size is 8 persons for CSA adopters, whereas it's 7 persons for non-adopters. In the female category, the average household size is 8 persons for CSA adopters and 9 persons for non-adopters. Moreover, a higher proportion of CSA adopters own the land they cultivate, with 93% of male adopters compared to about 44% of non-adopters, and 41% of female adopters compared to 32% of non-adopters. CSA adopters also tend to have larger farm sizes, with an average of 8.31 hectares among male adopters versus 7.06 hectares among non-adopters, and 4.45 hectares among female adopters versus 3.28 hectares among non-adopters. Furthermore, all CSA adopters are fully aware of various CSA practices, in contrast to 63% and 46% awareness levels among male and female non-adopters, respectively. Education level plays a crucial role in this context, as it signifies proficiency in farming skills necessary for leveraging improved technologies and achieving better yields. Previous impact assessment studies have consistently highlighted a positive correlation between education and the adoption of agricultural innovations (Ogunniyi et al., 2018). Similarly, the number of years of farming experience serves as an indicator of expertise in agricultural practices, thus expected to positively influence CSA adoption. The inclusion of these control variables in our models enables a more comprehensive understanding of the factors shaping households' adoption of CSA practices and their resulting welfare outcomes.

Table 2. Summary descriptive statistics by treatment

Variable	Male farming household				Female farming household			
	Full sample (N=335)	CSA Adopters (n=138)	Non-adopters (n=197)	Mean difference	Full sample (N=289)	CSA Adopters (n=122)	Non-adopters (n=167)	Mean difference
Outcome variables								
Total farm/crop yield (kg/ha)	4,372.49 (2,453.04)	5,370.39 (2,381.44)	3,553.05 (2,624.76)	1817.34***	3,088.96 (1,791.35)	3,989.37 (1,742.02)	2,314.63 (1,913.80)	1,674.74***
Per capita household income (₦)	80,610.30 (5,713.26)	95,121.67 (5,586.32)	69,389.15 (6,073.40)	25,732.52***	67,987.05 (6,529.89)	81,673.20 (6,495.78)	57,075.89 (6,830.52)	24,597.31***
Per capita food consumption expenditure (₦)	9,297.63 (4,774.48)	10,923.14 (4,600.73)	8,051.62 (5,143.10)	2,871.52***	7,533.89 (5,272.29)	8,598.74 (5,354.39)	6,776.55 (5,405.38)	1,822.19***
Control variables								
Age (years)	49.41 (16.50)	49.96 (16.97)	49.85 (16.37)	0.11	49.04 (16.17)	48.45 (15.95)	50.62 (16.71)	-2.17
Marital status (1=married, 0=otherwise)	0.87 (0.33)	0.82 (0.39)	0.93 (0.27)	-0.11	0.64 (0.48)	0.66 (0.47)	0.64 (0.49)	ne0.02***
Education (years of schooling)	8.44 (3.98)	8.78 (4.29)	8.28 (3.75)	0.50	6.87 (3.56)	7.57 (3.65)	6.30 (3.54)	1.27***
Household size (number)	7.37 (3.43)	7.96 (3.48)	6.93 (3.45)	1.03***	8.64 (4.38)	8.45 (4.12)	9.01 (4.72)	-0.56
Ownership of farmland (1=yes, 0=no)	0.68 (0.37)	0.93 (0.26)	0.44 (0.49)	0.40*	0.36 (0.49)	0.41 (0.50)	0.32 (0.48)	0.09*
Total farm size (ha)	7.61 (3.68)	8.31 (4.22)	7.06 (3.21)	1.25***	3.83 (3.01)	4.45 (3.17)	3.28 (2.91)	1.17***
Farming experience (years)	18.82 (13.03)	19.05 (12.77)	18.98 (13.56)	0.07	17.76 (10.55)	18.23 (11.06)	17.64 (10.25)	0.59
Membership of farmers' union (1=yes)	0.53 (0.49)	0.59 (0.50)	0.48 (0.50)	0.11	0.49 (0.73)	0.55 (0.51)	0.44 (0.97)	0.11
Extension service (number)	5.38 (4.80)	6.35 (5.47)	4.52 (4.23)	1.24**	2.79 (2.99)	3.23 (4.10)	2.40 (1.94)	0.83
Access to credit (1=yes, 0=no)	0.19 (0.35)	0.21 (0.39)	0.18 (0.32)	0.03	0.16 (0.39)	0.19 (0.39)	0.13 (0.41)	0.06
Awareness of CSA practices (1=yes, 0=no)	0.81 (0.24)	1.00 (0.00)	0.63 (0.48)	0.37***	0.72 (0.49)	1.00 (0.00)	0.46 (0.99)	0.54***
Access to climatic information (1=yes, 0=no)	0.53 (0.49)	0.65 (0.48)	0.42 (0.50)	0.23	0.32 (0.43)	0.49 (0.50)	0.15 (0.36)	0.34**
Access to agricultural training (1=yes, 0=no)	0.27 (0.41)	0.37 (0.43)	0.18 (0.39)	0.19	0.09 (0.28)	0.14 (0.35)	0.05 (0.21)	0.09
Distance to nearest market (km)	23.36 (20.71)	23.96 (20.61)	23.23 (21.22)	0.73	20.96 (17.03)	18.78 (16.47)	23.56 (17.93)	-4.78

**, **, ***represent statistically significant at 10, 5 and 1%, respectively.*

Source: Field survey (2023)

Determinants of adoption of CSA practices

Table 3 presents the factors influencing the adoption of CSA (Climate-Smart Agriculture) practices by households, along with their corresponding marginal effects. The results of the likelihood ratio test reveal the substantial significance of the model estimates at the 1% level for both male ($\chi 2$ = 148.62 (14), $p < 0.01$) and female ($\chi 2$ = 127.65 (14), $p < 0.01$) farming households. Examination of Equation 1 indicates that several factors exert a notable influence on the adoption of CSA practices among male farming households. These factors include household size, land ownership, overall farm size, farming experience, accessibility to extension services, availability of credit, awareness regarding CSA practices, access to climate-related information, and distance to the nearest market. Likewise, concerning female farming households, the findings presented in Table 3 demonstrate a significant association between CSA adoption and educational attainment, total farm size, farming experience, membership in farmers' unions, access to credit and climate information, and distance to the nearest market.

Table 3: Probit estimates of determinants of adoption of CSA practices

Variable	Male farming households				Female farming households			
	Probit regression		Marginal effects		Probit regression		Marginal effects	
	Coefficient	Std. error	dy/dx	Std. error	Coefficient	Std. error	dy/dx	Std. error
Age	0.0001	0.0021	0.0053	0.0081	0.0077	0.0083	0.0019	0.0001
Marital status	-0.1633	0.1605	-0.0833	0.0148	-0.2974	0.1026	-0.0044	0.0144
Education	0.2024	0.1510	0.0350	0.0121	0.1102***	0.0014	0.0161***	0.0370
Household size	0.0712**	0.0160	0.0321**	0.0060	0.4201	0.5402	0.0212	0.0011
Ownership of farmland	0.0164*	0.0130	0.0101*	0.2020	0.0061	0.0080	0.0062	0.0080
Total farm size	0.1172***	0.0282	0.0161***	0.0100	0.0630***	0.0130	0.0024***	0.0030
Farming experience	0.4930***	0.1364	0.0171***	0.0306	0.3781***	0.1291	0.0521***	0.0036
Membership of farmers' union	0.0715	0.0880	0.0326	0.0107	0.0194***	0.0896	0.0067***	0.0915
Extension service	0.0375**	0.0980	0.0009**	0.0010	0.2601**	0.1540	0.0381	0.0043
Access to credit	0.1074*	0.0531	0.0787*	0.0922	0.5140**	0.1870	0.015**	0.1010
Awareness of CSA practices	0.5340***	0.1190	0.0313	0.1211	0.3992***	0.1315	0.0108	0.0026
Access to climatic information	0.4428**	0.2130	0.0571**	0.0072	0.3250**	0.7090	0.0030**	0.0040
Access to agricultural training	0.1040	0.2110	0.0214	0.0017	0.3371	0.1212	0.0211	0.0012
Distance to nearest market	-0.0189*	0.0060	-0.0024*	0.0030	-0.0088*	0.0020	-0.0026*	0.0030
Constant	1.0688*	0.3241			0.4039*	0.2472		
Pseudo-R^2	0.255				0.0868			
LR chi2 (14)	148.62				127.65			
Prob>chi^2	0.0000				0.0000			
Number of observations	335		335		289		289	

**, **, ***represent statistically significant at 10, 5 and 1%, respectively.*

Source: Author's computation (2023).

Note: Robust standard errors reported.

The coefficient of educational level demonstrates a positive and statistically significant correlation with the propensity of female-headed farming households to adopt CSA practices. An elevation in educational attainment by one unit corresponds to a 0.0161 increase in the conditional probability of adopting CSA practices, indicating a 1.61 percent rise. This implies that as female household heads attain higher levels of education, their inclination towards embracing CSA practices escalates. The outcomes indicate that households headed by individuals with higher educational backgrounds are more inclined to adopt a greater number of CSA practices. These findings align with those of Sardar *et al.* (2021). Enhanced levels of education augment farmers' comprehension of the benefits associated with CSA practices, thereby stimulating their adoption. Additionally, Haq *et al.* (2021) noted that farmers with better educational backgrounds exhibit heightened awareness regarding the repercussions of climate change, prompting them to engage in more CSA practices to mitigate production losses.

The likelihood of adopting CSA practices shows a significant association with household size among male farming households. The marginal effect reveals that for every unit increase in household size, there is a 3.21% rise in the likelihood of CSA practice adoption among male-headed households. One plausible explanation for this phenomenon is that male farming households with larger sizes may possess an ample labour supply for cultivation, acting as a catalyst for expansion and necessitating the adoption of enhanced farming techniques. This discovery resonates with the findings of other studies on the determinants of improved agricultural technology (Asfaw *et al.*, 2012; Wossen *et al.,* 2018). Furthermore, the coefficient associated with land ownership exhibits a positive and statistically significant relationship with the adoption of CSA practices among male farming households. The marginal effect of land ownership indicates that for every unit increase in access to farmland, there is a 1.01% augmentation in the likelihood of CSA practice adoption among male-headed households. Conversely, total farm size exerts a significant and positive influence on the likelihood of CSA practice adoption for both male and female farming households. The marginal effects suggest that a unit increase in total farm size results in a 1.61% and 0.24% upsurge in the likelihood of households adopting CSA practices for male and female-headed households, respectively.

Social capital emerges as a pivotal determinant influencing individual farmers' choices regarding the adoption of advanced agricultural technologies. Our research highlights that membership in farmers' unions yields a positive and statistically significant impact on the likelihood of female-headed households embracing CSA practices. The marginal effect estimates illustrate that female farming households' affiliation with any farmers' group amplifies the probability of CSA practice adoption by 0.67%. Previous studies (Hailu *et al.*, 2014; Tefera *et al.*, 2016; Wossen *et al.*, 2017) have underscored that the uptake of improved technology experiences a notable surge if the household head is part of any association. Furthermore, the findings pertaining to institutional variables utilized in the model suggest that the adoption rate can be bolstered through support from relevant agencies. For instance, our analysis reveals that access to climate information exerts a positive and significant influence on the adoption of CSA practices among both male and female farming households. The marginal effect indicates that the probability of adoption escalates by 5.71% and 0.30% for male and female households, respectively, when they have access to climate change information. This outcome resonates with the findings of Sardar *et al.* (2021) and Awotide *et al.* (2022), who observed that farmers are more inclined to adopt CSA practices in the presence of information regarding the detrimental impacts of climate change.

Moreover, access to credit and extension services emerges as influential factors positively impacting the adoption of CSA practices across genders. The results suggest that male and/or female farming households endowed with productive resources such as credit facilities and equipped with knowledge, skills, and awareness regarding CSA practices through extension services are more predisposed to adoption compared to those lacking such support. Previous studies (Mahama *et al.*, 2020; Nkegbe and Shankar, 2014; Awuni *et al.,* 2018; Awotide *et al.,* 2022) have corroborated that access to credit facilities and extension services plays a pivotal role in shaping farmers' attitudes and decisions regarding the adoption of agricultural technology. Also, distance to the nearest market emerges as another crucial factor with a negative influence on the adoption of CSA practices among farming households, irrespective of gender. The marginal effect reveals that for each incremental unit of distance to the nearest market, the probability of CSA practice adoption diminishes by 0.0024% and 0.0026% for male and female-headed households, respectively. This implies that households situated farther away from output markets or agricultural centers, where farm produce is typically traded, are less inclined to utilize or embrace CSA practices. This impact is statistically significant at the 1% level, echoing the findings of Wang *et al.* (2020), who underscore the significance of proximity and connectivity with agricultural hubs in augmenting the likelihood of selling agricultural products and achieving higher profits, thereby facilitating the adoption of enhanced agricultural technologies.

Distributional impact of adoption of CSA practices on farm and welfare outcomes

Table 4 illustrates the impact of adopting CSA practices on farm and welfare outcomes as investigated in this research, categorized by gender. These outcomes comprise total farm/crop yield (measured in kg/ha), per capita household expenditure, and per capita expenditure on food. The results indicate a positive and statistically significant effect of CSA adoption on total farm/crop yield across various quantiles and genders of household heads, with the exception of the 25th percentile among female-headed farming households. Specifically, the influence of CSA adoption ranges from 4.839 kg/ha to 10.104 kg/ha among male-headed farming households and from 3.481 kg/ha to 9.809 kg/ha among female-headed farming households, across different quantiles. These findings highlight a noteworthy variance in the impact of CSA adoption on overall farm productivity, as measured by farm/crop yield, across different segments of the population distribution. Nevertheless, a significant difference exists in the effect of CSA adoption on total farm/crop yield between male and female farming households, with male-headed households demonstrating more favourable outcomes compared to their female counterparts.

In farming households led by men, adoption of CSA practices results in significant enhancements in farm/crop yield across various levels of income. Specifically, there are substantial increases, ranging from 50.72%, 43.05%, to 36.47% for households positioned at the 15th, 25th, and 50th percentiles, and from 29.68% to 23.92% for those at the 75th and 85th percentiles, respectively. This indicates that the impact of CSA practices adoption on farm/crop yield is more pronounced among economically disadvantaged male-led farming households compared to those that are more better off. Likewise, in households led by women, embracing CSA practices leads to significant yield improvements across different outcome levels. The enhancement varies from 54.01% to 25.86% for households at the 15th and 50th percentiles, and from 20.47% to 16.31% for households at the 75th and 85th percentiles, respectively. This suggests that the influence of CSA practices adoption on farm/crop yield is more noticeable among economically disadvantaged female-headed farming households compared to those that are more financially stable. These findings align with those of Sanglestsawai et al. (2014) regarding the yield impact of Bt corn in the Philippines. They indicate that the benefits of adopting Bt corn, similar to CSA practices, are particularly significant among farmers with lower yields, highlighting a 'pro-poor' aspect to the adoption of such technologies.

Table 4: Distributional effect of adoption of CSA practices on farm and welfare outcomes

Variable	Male farming households					Female farming households				
	IV-QTE estimates									
	Q0.15	Q0.25	Q0.50	Q0.75	Q0.85	Q0.15	Q0.25	Q0.50	Q0.75	Q0.85
Total farm/crop yield ('000kg/ha)										
Treatment effect of adoption	4.839*** (1.635)	6.920*** (1.882)	8.745*** (2.362)	10.291*** (3.517)	10.104* (3.953)	3.481*** (1.309)	5.282 (1.553)	7.047*** (2.158)	9.145*** (3.361)	9.809** (3.574)
% impact of adoption	50.72	43.05	36.47	29.68	23.92	54.01	39.50	25.86	20.47	16.31
Per capita household income (₦' 000)										
Treatment effect of formal education	10.192*** (3.537)	12.765*** (4.032)	15.283*** (4.740)	22.547*** (6.183)	29.611*** (10.357)	8.537** (3.149)	13.098*** (5.461)	19.245*** (7.278)	24.503*** (10.167)	32.442*** (10.851)
% impact of formal education	85.16	57.92	33.21	26.98	20.53	82.40	46.78	39.41	32.69	24.82
Per capita food consumption expenditure (₦' 000)										
Treatment effect of formal education	13.507** (3.182)	15.112*** (3.670)	18.453*** (4.462)	22.058*** (5.257)	27.319** (8.414)	10.572** (3.051)	14.846*** (5.305)	19.214*** (8.172)	25.575*** (11.394)	31.001*** (12.136)
% impact of formal education	93.05	60.98	45.56	36.24	29.83	86.42	56.89	44.20	38.08	29.67

Note: The figures in parentheses are standard errors.

*, **, ****represent statistically significant at 10, 5 and 1%, respectively.*

Source: Author's computation (2023).

The findings indicate that adoption of CSA practices has a significant and positive effect on both the per capita household income and the per capita food consumption expenditure across different quantiles and gender of the household heads. In households led by men, this impact ranges from ₦10,192 (Q0.15) to ₦29,611 (Q0.85) for per capita household income and from ₦13,507 (Q0.15) to ₦27,319 (Q0.85) for per capita food consumption expenditure. For female-headed farming households, the effect varies from ₦8,537 (Q0.15) to ₦32,442 (Q0.85) for per capita income and ₦10,572 (Q0.15) to ₦31,001 (Q0.85) for per capita food consumption expenditure. Notably, the most substantial increases in both per capita income and food consumption expenditure occur at the lower ends of the outcome distribution. For instance, in male-headed households, adopting CSA practices increases per capita household income by 85.16% and 57.92% at the 15th and 25th percentiles, respectively. Similarly, for female-headed households, it boosts per capita household income by 82.40% and 46.78% at the same percentiles. These patterns align with previous research, such as Awotide *et al.* (2022), which observed enhanced welfare outcomes among the poorest when adopting climate-smart agricultural technologies in Mali. Similarly, Olagunju *et al.* (2020) noted more pronounced positive effects on the welfare of poorer maize farmers in rural Nigeria through the adoption of improved seed varieties. However, the impact of CSA adoption is notably higher in male-headed households compared to female-headed households, affecting both per capita income and per capita food consumption expenditure. This variation in outcomes between male and female-headed farming households may arise from several factors considered in the analysis.

Conclusion

While prior research has delved into the influence of implementing CSA practices on agricultural output, there is still a lack of understanding about the various and complex effects of CSA adoption by gender of household heads. This research endeavors to fill this void by meticulously examining gender disparities and the distributional impact of CSA adoption, with a specific focus on agricultural productivity and welfare outcomes. Through the scrutiny of gender-segmented data collected from a sample of rural farming households in southwest Nigeria, we employ instrumental quantile treatment effects (QTE) econometric techniques to unveil insights that account for potential biases stemming from both observable and unobservable factors.

Our investigation underscores several key factors that exert a notable influence on the uptake of CSA practices within farming households led by men. These factors encompass household size, land ownership, overall farm size, farming experience, access to extension services, access to credit, awareness of CSA practices, access to climate-related information, and proximity to the nearest market. Similarly, regarding farming households headed by women, the results reveal a significant correlation between CSA practice adoption and educational level, total farm area, farming experience, participation in farmers' associations, access to credit and climate-related information, and distance to the nearest market. The significant differences in the determinant factors underscore the importance of enhancing the assessment of each variable identified.

In particular, our preferred model, IV-QTE, indicates significant differences in the effects of CSA practice adoption across gender lines. Male-headed households tend to benefit more favourably compared to their female-led counterparts in terms of both farm productivity (yield per hectare) and welfare distributions. This highlights a notable discrepancy in how CSA adoption influences different economic segments within households. Essentially, the impact of CSA practice adoption on farm yield is particularly pronounced among economically disadvantaged farming households, regardless of gender, compared to wealthier ones. Furthermore, there exists a significant disparity in how CSA adoption affects total farm/crop yield between male and female-headed farming households, with male-led households achieving better results. Similarly, the most substantial percentage increases in the impact of CSA adoption were observed at the lower ends of per capita household income and food consumption expenditure distributions for both male and female-headed households. Thus, our analysis indicates that the positive effects of CSA practice adoption on the welfare of farming households are more evident among economically marginalized households than among financially stable ones, regardless of the gender of the household head. However, a significant gender gap persists even among economically disadvantaged households led by both males and females, as well as within financially secure households led by both genders.

Our research offers empirical evidence supporting the efficacy of CSA adoption as a remedy for the prevalent issue of low productivity, particularly among impoverished households, irrespective of gender. Embracing CSA practices not only results in notable increases in crop yields and overall welfare but also underscores the pressing need for governmental bodies at various levels to promote CSA adoption through robust advocacy, training programs, and diverse extension services, especially among resource-constrained farming households currently grappling with the adverse impacts of climate change. By doing so, we can not only address the gender disparity in CSA adoption but also substantially bolster agricultural productivity and the welfare of farming households. Furthermore, our study unveils a significant difference in CSA adoption rates between households led by men and those led by women, emphasizing the imperative of empowering female-headed farming households to ensure parity with their male counterparts. These initiatives are crucial for bridging the gender gap and fostering gender equality in CSA adoption, thereby amplifying adoption rates, enhancing farm output, and elevating household welfare.

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Empowering Women and Youth in Agribusiness Through Knowledge Management Practices Under Sustainable Agriculture Production Programme (SAPP)

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Abstract

The agriculture sector in Malawi accounts for about 25 percent of Malawi's GDP and over 80 percent of the country's food crop is produced by smallholder farmers. Most of the smallholder farmers in Malawi are women, who perform most of the agricultural tasks. However, Malawian men have typically been prioritized over women in agricultural production, creating gender inequality. Among other factors, gender inequality in Malawi is reinforced by lack of access to resources (land, labor, and capital), economic dependence, and high illiteracy levels

Smallholder production is characterized by low production levels due to low levels of farm inputs and low outputs, dependency on rain fed production, limited capital due to inadequate access to credit, high interest rate and interest rate spreads, high transport costs and limited access to reliable markets. Livestock production is characterized by subsistence grazing of cattle, goats, poultry, and pigs. Malawi is particularly vulnerable to climate change due to high reliance on natural resources. Malawi is experiencing more frequent extreme events like droughts, floods, parasites, and disease attacks. These have adverse economic impacts for women farmers, with Malawi losing, on average, 1.7 percent of its GDP due to the combined effects of climatic change.

To ensure access to agricultural information the Ministry of Agriculture communicates to farmers through varied methods including print (leaflets, posters, magazines) and electronic (radio, cine films, email, Facebook, YouTube and WhatsApp) media. Frontline staff disseminates all information including on climate smart agriculture practices; gender in agriculture as well as agribusiness related messages. The paper therefore highlights strategies to empower women and youth farmers to overcome the challenges through knowledge management practices as implemented by an IFAD-funded programme called Sustainable Agriculture Production Programme (SAPP).

The Ministry of Agriculture implemented SAPP from December 2011 to March, 2023. Its objective was to contribute to reduction in poverty and improved food security among the rural population in order to achieve a viable and sustainable smallholder agriculture sector employing Good Agricultural Practices (GAPs). Across all the programme components, SAPP empowered women and youth farmers through building their capacity in agribusiness, climate smart agricultural practices and provision of technical and financial support and incorporated interventions in addressing the gender gaps.

This was achieved by working with groups comprising men and women, and deliberately targeting women and youth groups separately. All the interventions promoted in the programme proved successful as over 86 percent of women farmer groups and 72 percent of youth groups supported by the programme have sustained all the interventions even after SAPP phased out. Case studies, success stories and lessons learnt from the programme were developed in line with women and youth empowerment interventions.

This paper therefore recommends that when addressing gender gaps, projects and programmes should focus on gender empowerment programmes with deliberate efforts targeting women and youth groups through capacity building in different areas of production and marketing, including provision of technical support to ensure self–reliance. Additionally, knowledge management

and communication is another important aspect which should not be ignored in achieving project goals.

Key Words: Agribusiness, strategies, smallholder farmers, empowerment, sustainability, knowledge management, communication, SAPP, women and Youths

Introduction

The agriculture sector in Malawi accounts for about 25 percent of Malawi's Gross Domestic Product (GDP). Over 80 percent of the country's food crop is produced by smallholder farmers. Most of the smallholder farmers are women farmers who perform most of the agricultural tasks, but Malawian men, have typically been prioritized over women in agricultural production. This situation creates gender inequality. Gender inequality in Malawi is reinforced by lack of access to resources (land, labor, and capital), economic dependence, and high illiteracy levels, among other factors. [5]

Smallholder production is also characterized by low production levels due to low levels of farm inputs and low outputs, dependency on rain fed production, limited capital due to inadequate access to credit, high interest rate and interest rate spreads, high transport costs and limited access to reliable markets.

Livestock production is characterized by subsistence grazing of cattle, goats, poultry, and pigs. The country is particularly vulnerable to climate change due to high reliance on natural resources. Malawi is experiencing more frequent extreme events such as drought, floods, parasites, and disease attacks. On average, 1.7 percent of its GDP is lost due to the combined effects of climatic change and this has adverse economic impacts for women farmers.

Some of the challenges these women farmers face includes lack of access and control over land. Thus although they perform 50 –70 percent of all agricultural tasks, women rarely have control over the land. Female-managed plots are, on average, 12 percent smaller than those of their male counterparts and 25 percent less productive as a result of differing levels of knowledge and access to inputs for improving farming efficiency [1]. This negatively affects production levels for women.

In addition to land, women's role in agriculture is typically constrained by other key factors like lower education levels, lesser control over natural resources, reduced labour availability (due to gender roles which govern their role in caretaking) and minimal access to financial resources. Together this limits their knowledge of improved production practices, access to farm inputs (including fertilizers and improved seeds) and labour-saving technologies (such as ploughing machinery), and the ability to practice more labour-intensive farming methods. These differences also have the potential to be exacerbated by climate change and negatively affect their yield. [5]

Malawi's agriculture is largely rain fed, particularly among smallholders, and the country is at critical risk of water stress. Water security is essential for agriculture in a changing climate, but women typically have lower levels of access than men in water technologies, such as irrigation. The result is differing levels of productivity of men and women farmers.

Knowledge Management and Communication in Agriculture faces a number of challenges in Malawi and in the Ministry of Agriculture in particular. Implementation and uptake of Knowledge Management and Communication (KMC) practices like Information Education and Communication (leaflets and newsletters) and electronic materials (radio, and TV programs) and ICT based platforms such as messages through mobile phones remained relatively poor due to social and economic impediments that women and youth farmers faced. Culturally, in villages, men are perceived to be the owners of household equipment like radio sets and therefore the primary users who choose what the family listens to. If the men don't tune in to farming programs or they decide to go away with the radio set, the women and youth miss out. The same applies to mobile phones. Men own the only phone in the home and women and youth rarely have access to benefit from farming and agriculture messages.

Another biggest challenge is illiteracy levels as most women can neither read nor write. This made it difficult to attract women to Agriculture Resource Centers (ARCs) where extension information is accessed through reading.

The Ministry of Agriculture through DAES strives to achieve its objectives through the use of the District Agriculture Extension Service System (DAESS) and different approaches and concepts. Some of the approaches and concepts the department uses are; Model village approach, integrated homestead farming, household approach, farmer field school, farm business school, lead farmer approach, agricultural resource centers, and multimedia approach, just to mention a few. The department recognized the importance of managing the above various approaches and systems within the department and various stakeholders in the agriculture extension for attainment of policy objectives in the agriculture sector and Malawi as a country. However, there is a knowledge gap within the department and beyond the agriculture extension sector on how to process, store and manage the knowledge generated through the DAESS and its approaches. The vast knowledge on agriculture extension has not been nurtured, processed, stored and passed to various stakeholders for future use.

The Sustainable Agriculture Production Programme (SAPP) has been implementing its Knowledge Management and Communication Strategy through the Department of Agriculture Extension Services (DAES) which is under the Ministry of Agriculture.

About the Sustainable Agriculture Production Programme (SAPP)

The Ministry of Agriculture implemented the Sustainable Agriculture Production Programme (SAPP) from December 2011 to March, 2023. The programme's objective was to contribute to poverty reduction and improved food security among the rural population in order to achieve a viable and sustainable smallholder agriculture sector by employing good agricultural practices (GAPs) [6]. Across all the programme components, SAPP empowered women and youthful farmers through building their capacity in agribusiness, climate smart agricultural practices and provision of technical and financial support (through grants), and also incorporated interventions in addressing the gender gaps. This paper therefore, highlights the roles of women in agriculture focusing on SAPP successes in areas of women and youth empowerment, access to financing and markets through knowledge management practices

The main objective of the paper is to investigate how women and youth in Agribusiness were empowered through Knowledge Management and Communication (KMC) practices under SAPP.

Specifically, the paper intends to find out about the Knowledge Management and Communication Practices under the Ministry of Agriculture with reference to SAPP; assess the effectiveness of the Knowledge Management and Communication Practices under SAPP; examine how farmers, receive messages and provide feedback on agribusiness under SAPP; analyze the participation of youth and women farmers in accessing agricultural markets under SAPP and investigate how farmers access financing for improved livelihood under SAPP

Methodology

The development of this paper was based on analysis of documents, systems, and key informant interviews with different subject matter specialists in the Department of Agriculture Extension Services and individual discussions on a need basis. These are the key stakeholders in the implementation of the programme. The programme was implemented in 46 Extension Planning Areas (EPAs) in six districts of Malawi; Chitipa in the Northern Region, Lilongwe and Nkhotakota in the Central Region, and Balaka, Blantyre and Chiradzulu in the Southern Region. The programme gave specific attention to promoting women and youth participation in programme activities. Women and youth were targeted to receive GAP technologies, training and extension services, amongst others. In addition, the programme targeted to develop and release four GAPs that were intended at reducing labour for women. The project log frame provided quantitative targets for the number of women and youth receiving programme services and these were set at 50 percent and 25 percent, respectively. The monitoring and evaluation system was calibrated to track and analyze sex and age disaggregated data.

The paper also highlights women and youth empowerment approaches that were used by the programme through a case study of a farmer group conducted through a focus group discussion in Lilongwe District in Malingunde Extension Planning Area (EPA) under Traditional Authority Masumbankhunda.

Study Design

The study is designed to use the already existing data captured, documented and published throughout the implementation of SAPP. These include baseline data through baseline surveys conducted before implementation of the programme, midterm survey reports, annual reports, and annual outcome survey report and also project completion report (PCR)

Results and Discussion

SAPP promoted women's empowerment by involving them in various interventions using various innovative extension approaches and concepts. The programme further ensured that there was equitable participation and involvement of all gender categories in decision making, asset ownership, agribusiness activities, and leadership. The programme ensured that women are involved in decision making and own productive assets. The programme's Project Completion Report (PCR) indicated that 91 percent of women were involved in making decisions on agribusiness activities, 87 percent on the use of land, and 72 percent on making a decision on which crop enterprise (to grow). In addition, the results showed that 83 percent of women owned land. This implies that SAPP maintained the effort on involvement of women in making decisions on control and access to various resources. This shows a significant contribution to the achievement of the Malawi National Agricultural Policy of 2016, [9] which aims at increasing women's access to, ownership of, and control of productive agricultural assets by 50 percent. The large involvement of women in decision making might be attributed to capacity building of farmers in Household Approach which SAPP promoted to ensure equitable access to and control over resources, assets and benefits at household level. SAPP used household approach to address underlying root causes of gender disparities. This is reflected in the target group sampled for this study.

Case: Empowered farmer group supported by SAPP through Knowledge Management and Communication

- Kachenga Cooperative

The cooperative started as a farmer club in June, 2017 to address rampant challenges faced in the members' farming businesses including challenges faced by women and youth farmers of the group.

The group covers farmers from four sections of Malingunde Extension Planning Area (EPA) namely: Nachikompha, Namsulu, Mphangwe and Naminyanga.

Initial membership for the group in 2017 was 50 members (19 Males; 31Females; and 44 youths).

The overall objective of the cooperative is to assist its members in improving their living standards through farming businesses thereby contributing to poverty eradication in the area.

The group has an active and dedicated leadership which strives to assist its members in achieving their vision and is led by a woman.

Currently membership has increased to 102 members (30 Males 30; 72 Females; and 81 youths) representing 70 percent women and 79 percent youths.

In 2018, with support from SAPP, Kachenga Cooperative was trained in farm business school concept where members acquired farm business management skills, farm production skills, business management skills and financial management skills.

The cooperative was registered in 2021 with support from SAPP.

The group engages in production and marketing of soybeans, groundnuts, maize and goat-keeping. They also engage themselves in manure making and utilization for improved soil fertility.

- The group engages in trade where they buy from other smallholder farmers and sell to other markets like Fairway Enterprises, Market Link Support (MLS), Sun Seed Oil, and Agriculture Commodity Exchange (ACE). They continue to reach out to these markets even after SAPP phased out.
- Despite all the efforts, the group faced challenges of low production and productivity of these value chains and decided to apply for a US$ 2,235 (MK 3,800,000.00) grant under SAPP to increase their production capacity.

- The purpose of the grant was to increase production and productivity of soybean, groundnuts and maize through procurement of seed and goats to assist in increasing manure making and utilization for improved fertility.
- The grant was used to procure soybean seed worth US$ 470 (MK 800,000.00) and 150 goats worth US$ 1,765 (MK3, 000,000.00) which was shared amongst the members. Each member received 5 goats, and was provided to the first original 30 members of the group. They agreed to pass on the goats within the membership.
- Members constructed goat pens as their own contribution to the grant received.
- To date, all the cooperative's 102 members own goats and each member make an average of 8 metric tons of compost manure, which they use in their maize and legume fields. This has also assisted the members to adapt and mitigate effects of climate change and increased their crop yield.
- They also started bulk selling of the goats and so far a total of 111 goats have been sold to local traders.
- To date, the cooperative owns 708 goats, with an average of 7 goats per member.
- Production of soybean has significantly increased from 12 metric tons to over 32 metric tons with the initial seed they procured under SAPP. To sustain the programme, they engage in resource mobilization where they mobilize funds for bulk procurement of farm inputs. This has assisted them in sourcing seed from reputable seed suppliers and the farmers are assured of good quality seed. Progress on funds mobilization is as follows:
    - 2021/22 season – Mobilized US$ 465 (MK790, 000.00)
    - 2022/23 season – Mobilized US$ 1000 (MK1,700,000.00)
    - 2023/24 season – Mobilized US$ 3,141 (MK 5,340,000)
    - 2024/25 Season - The group is in the process of mobilizing funds for the coming season

Successes for the group:

- The group managed to increase their share value from US$ 29 (MK50, 000.00) to US$ 58 (MK100, 000.00) per member and all members have already bought the shares.
- Through the proceeds realized, Kachenga Cooperative bought 1-acre piece of land in Mphangwe section worth US$ 1,470 (MK2, 500,000.00) where they intend to construct a warehouse and factory for the cooperative, which is in line with their vision.
- Annually, they rent 3 hector (ha) piece of land for production of soybeans and groundnuts for the whole group to increase on individual production levels.
- Other farmers joined the cooperative because they saw how members benefitted. Membership increased from 50 to 102 members, and more farmers continue to join.

Successes for individual members for the group:

Through their businesses and improved capacities through SAPP, Kachenga Cooperative members realized significant benefits as follows:

- 28 members have managed to construct iron sheet roofed houses, a milestone they never imagined they could ever achieve. A case in point is the cooperative's Chairperson, Lucy Mandevu who constructed an iron roofed house after realizing significant profits from soybean, maize and goat sales for two consecutive years.

Lucy Mandevu showing off her house

- 8 members managed to procure 20 pigs
- 15 members managed to procure 7 dairy cattle
- 6 members procured motorcycles
- Members regularly paid school fees for their children and other relations. Case in point is Mrs. Anna Pazingezi Josiah, Kachenga Cooperative Discipline Sub-committee member who received 5 goats from the cooperative under the SAPP supported Village Challenge Fund (VCF) and now owns 15 goats and 5 pigs. She and her family can now harvest over 10 metric tons of maize, 8 metric tons of soybeans, and 12 metric tons of groundnuts as a result of compost manure making and utilization. She can pay school fees for her four children, two of whom are in college and the other two in secondary school.

Mrs. Anna Josiah in front of her goat pen

Alepha Nkhondo, a member of Kachenga Cooperative from Malingunde EPA, Lilongwe district who is able to provide all basic needs for her family.

Almost all members of Kachenga Cooperative (including all the women and youth farmers) can provide basic needs for their families throughout the year from proceeds and benefits realized from the cooperative. Members are hopeful for a better future for themselves and their families.

Knowledge Management (KM) Practices in the Ministry of Agriculture – DAES & SAPP

There have been efforts in ensuring access to agricultural information by the Ministry of Agriculture and SAPP implemented the ministry's Knowledge Management and Communication strategy through DAES. The Ministry communicates its messages to the farmers through the Agriculture Communication Branch (ACB), which is within DAES. Communication is done using various methods, including print (leaflets, posters, magazines) and electronic (radio, cine films, email, Facebook, YouTube, WhatsApp and ICT based communication). The ACB disseminates agriculture information to farmers through the extension frontline staff. These messages are produced and packaged at DAES and distributed across all districts in Malawi for farmers use.

The ACB complements efforts of dissemination of agriculture information to farmers through the extension workers who in most cases cannot manage to visit every farmer. Extension-farmer ratio in Malawi is 1:3500 against the recommended ratio of 1:750. This shows the need to complement extension workers' efforts for dissemination of agriculture information to succeed. The disseminated information includes information on climate smart agriculture practices; gender in agriculture as well as agribusiness related information among others.

The SAPP programme implemented a number of Knowledge Management and Communication activities during its eleven-year implementation period. The following sections outline an analysis of the activities and impact. These approaches in knowledge management led to the success of Kachenga Cooperative in Malingunde, Lilongwe, Malawi.

Analysis of KM activities and its impact under SAPP

Establish and Strengthen Agriculture Resource Centers (ARCs)

To build farmers' capacity in various Good Agriculture Practices (GAPs) at all levels, DAES established and strengthened resource centers for farmers to access information on various GAPs through harmonized mounted demonstrations and mini libraries. By the end of the project implementing period (2022/23), a total of 30 agriculture resource centers were established against the annual target of 50 representing 60 percent achievement. The programme cumulatively established 274 out of 92 resource centers that were planned to be established representing 298% achievement [7]

Immediate Outcome

There was an increase in the number of people, including women accessing the resource centers. Farmers were able to access various extension messages hence helping in dissemination of Good Agriculture Practices. ARCs are also a meeting place for farmers where they are able to share information and experiences. [7]

Produce Information Electronic and Communication (IEC) Materials (Posters, Leaflets, DVDs and TV Documentaries)

Production and dissemination of IEC materials increased the number of farmers reached with extension messages on Good Agricultural Practices. During the project's implementation period DAES and the Ministry of Information produced video documentaries and aired them on local television stations such as the Malawi Broadcasting Corporation (MBC), Luntha, Mzati, Chancellor College, and Angaliba. The documentaries were also uploaded on the DAES and SAPP YouTube channels. Among other topics, the documentaries covered youth and women, agribusiness, household approach, Good Agricultural Practices, Village Challenge Fund, agroforestry, Rural Stimulus Facility, livestock pass-on programme and conservation agriculture [7].

At project closure, 242,342 IEC materials had been produced and distributed against a target of 150,000. This represents a cumulative achievement of 161 percent. Through the IECs farmers received extension messages on good agricultural practices, marketing, and gender and household approach [7].

Production and broadcasting of radio and TV programmes

To promote farmers' access to information on Good Agricultural Practices, SAPP through DAES conducted radio interviews in all SAPP districts. Radio and television programmes were produced and aired on MBC Radio, Zodiak Radio and TV, Times Radio and TV, and Beyond FM. Cumulatively the DAES managed to achieve 1,674 radio programmes against 832 representing 201percent.

Outcome:

Radio and television programmes produced assisted in disseminating various extension messages to farmers and rural communities on GAPs, Gender, Agribusiness practices and messages on COVID-19 pandemic adaptation mechanisms for farmers. This promoted adoption of Good Agricultural Practices across the districts, including hard-to-reach areas. Messages reached a wide coverage and those who were illiterate, could understand the various technologies promoted by the ministry. In addition, other farmers were mobilized into radio listening groups to discuss and practice the massages [7].

Conduct mobile unit campaigns

Through DAES, SAPP conducted mobile van campaigns to increase coverage of extension messages and adoption of good agricultural practices. The campaigns were on diverse topics, including early garden preparation, nutrition, manure making and application, vaccination of goats and chickens, fall armyworm management, post-harvest handling and food budgeting. Cumulatively the project achieved 330 out of 384 mobile campaigns, representing 86 percent [7].

Immediate Outcome

Campaigns have changed behavior of farmers, enhanced adoption of good agricultural practices and also reduced damage of crops due to fall armyworm. Implementation of mobile campaigns, however, had been affected by the COVID-19 pandemic, since campaigns normally attract a lot of people which was against the rules of COVID-19 prevention.

Document and disseminate best practices on GAPs and extension approaches through seminars, community of practice and workshops

To ensure effective knowledge management of best practices and GAPs, the programme documented and disseminated best practices on GAPs and extension approaches through community practices and workshops. Cumulatively the programme documented 298 best practices out of an appraisal target of 124 representing 240 percent. These best practices were on youth and women participation in agriculture, agribusiness, Conservation Agriculture, improved cooking stoves, promotion of GAPS through Farmer Field Schools (FFS), household approach, harmonized demonstration, Integrated Homestead Farming (IHF) and Village Challenge Fund [7].

SAPP Secretariat with support from IFAD under the Digital Advisory Support Services for Accelerated Rural Transformation (DAS) Program provided technical support for Information Communication for Development (ICT4D) activities within IFAD-financed programs. The DAS Program's main objectives were to: increase access to information and inclusive financial services for smallholder farmers, and increase the use of ICT4D solutions to achieve better targeting, monitoring, and impact measurement for agricultural development. The DAS Program partners are a consortium including Development Gateway, Jengalab, and TechChange. Under the terms of this specific engagement, IFAD's Malawi portfolio included a number of programs, both new and ongoing, that integrated various ICT tools (mobile applications, web-based platforms, etc.). Some of these programs include Sustainable Agriculture Production Programme (SAPP), Transforming Agriculture through Diversification and Entrepreneurship (TRADE), Financial Access for Rural Markets, Smallholders and Enterprise Programmes (FARMSE), and Programme for Rural Irrigation Development (PRIDE).

Support for SAPP included:

- Detail the user journey for users of Ulimi ndi nyengo (farming and weather) ICT app, including identifying design improvements to the user experience/interface
- Map potential partners for sustainability, especially agricultural institutions, and organizations that might need to adopt this solution for their farmer networks (TBC based on the field mission logistics and duration)
- Development of a digital training platform with accompanying digitized training to train extension workers

Immediate Outcome

Documentaries and ICT4D tools have increased adoption of best practices and GAPs among farming households and increased yield of the farm produce. ICT4D tools also have helped in bridging the farmer-extension ratio[7].

Train staff on knowledge management

The programme trained staff at various levels on how to document case studies and success stories, best practices, impacts and outcomes of the SAPP project. Out of the target of 240 staff, 267 have so far been trained in KM translating to 111 percent achievement. As a result of the training, the districts documented lessons learnt, case studies and successes of the programme which were included in the reports.

Lessons Learnt in Implementation of KMC Under Sapp in Empowering Women Farmers

The KMC strategy must be produced and begin to be implemented at the onset of a project. SAPP recruited the KMC officer after Mid Term Review (MTR). A lot of the project's successes were missed in the process.

A combination of traditional media (Print and electronic) and digital media is a powerful tool in reaching out to farmers and helps to bridge the farmer-extension ratio gap.

Radio is one of the most powerful tools for reaching out to farmers. Radio was reported to be relatively cheaper than print and one of farmers' preferred ways of receiving information. Farmers gave feedback through phone-in programmes, thereby encouraging a two-way communication.

There was increased adoption of good agricultural practices among the smallholder farmers in communities that accessed Agriculture Resource Centers (ARCs). The SAPP established ARCs in the six districts, mounted demonstration plots showcasing various crop varieties, crop practices and management, pest control, and management. The ARCs conducted field days at least three-times for the technologies that they demonstrated on the mounted plots. During the field days, farmers were asked to choose preferred technologies and practices favorable to their local condition and their context. The following year results showed that half of the farmers who attended field days in the previous season adopted one or more practices and crop varieties which were demonstrated during field days.

In Chiradzulu District in Thumbwe, Mombezi and Mbulumbuzi EPAs in the 2017/2018 season, demonstration plots were mounted on crops and different practices. The demonstrations were on manure making and application, herbal garden, cotton, pearl millet, orange fresh sweet potato varieties, contour marker ridge and ridge alignment, maize varieties and agro-forestry. In 2018/2019 season, out of 3820 farmers who accessed resource center services in the previous season, two thirds of them made manure and applied in their fields, one third planted pearl millet, half planted orange-fleshed sweet potato, and two thirds grew early maturing and drought tolerant maize varieties.

In Lirangwe EPA, Blantyre District, farmers adopted various technologies and practices based on demonstrations mounted by the resource center in 2017/2018. In the 2018/2019 growing season, the EPA experienced an increase in the number of adoptions as follows; 66 farmers (21 males and 45 females) adopted double-up legume-soya technology, 104 farmers (33 males and 71 females) adopted maize inter-planted with pigeon peas, 127 farmers (55 females and 72 males) groundnuts inter-planted with p/peas and 82 farmers (31 males and 51 females) adopted soya inter-planted with pigeon peas.

Adoption of good agricultural practices and technologies without interfacing with extension workers for farmers accessing ARCs

In Lilongwe East, 1683 farmers (632 males, 1051 females) across six EPAs of Chitsime, Mpenu, Chitekwere, Chigonthi, Nyanja and Mkwinda have adopted various technologies and practices without direct contact with extension workers. For instance, in Nyanja EPA, 15 female farmers started small stock farming after reading a publication on poultry farming. In the same EPA, more than 300 farmers are doing conservation farming after reading the literature of conservation farming. More than 41 farmers have started agro-forestry after reading about agro-forestry. The farmers formed a group and established a tree nursery by using a guiding manual of tree nursery establishment they found in the resource center library.

Farmers finding markets through ARCs

Some EPAs erected market information board for different commodities within their locality and neighboring districts. The information helped farmers to make informed decisions on where and when to sell their commodities. Mr. Rajabu Joni from Chiwundo Village T/A Namkumba, Ulongwe EPA in Balaka District is one of 300 farmers who have found markets through ARCs in Balaka. In 2016/2017 season Rajabu Joni started visiting the SAPP supported Namkumba resource center in Utale EPA with the aim of accessing agricultural information and he came across market information for different crops within the district and neighboring districts. He started following markets where he could sell produce at higher prices instead of waiting for traders to come to his village to dictate prices. The commodity traders were offering MK90 for a kilogram of maize, but Rajabu Joni sold his maize at MK220 per Kilogram in 2017/2018 season.

Recommendations and Conclusion

SAPP has been a success in Malawi in empowering farmers including women and youths through knowledge management practices. All the interventions promoted in the programme proved successful as farmer groups, including women farmer groups and youth groups supported by the programme sustained all the interventions, even after the program phased out. The paper, therefore, recommends that in addressing the gender gaps, projects and programmes should focus on gender empowerment through building of capacity in different areas of production and marketing. Projects and programmes should also provide technical support to ensure self–reliance through knowledge management and communication practices because this is an important aspect not to be ignored in achieving project goals.

Conclusions and recommendations on knowledge management under SAPP can be presented as follows:

- The SAPP programme generated much knowledge which influenced policy and contributed to the success of youth, women and agribusiness in Malawi.
- Knowledge has been captured from projects, consultants, social media platforms, events, communities of practice and shared and disseminated through lessons learnt booklets, conferences, reports, meetings, seminars, radio and television documentaries.
- Knowledge generated through SAPP is stored in personal computers and hard drives. There is no systematic way of storing the information on a platform that can be accessed by all. There is need to link the project's Management Information Systems with the Agriculture National Management Information System (NAMIS) to ensure secure access to management of data, even after closure of projects.
- There is a culture of working in silos and hoarding of information. This is detrimental to KM practices and can hinder KM work. There is need to encourage knowledge sharing sessions platforms.
- Projects and programmes within the Ministry of Agriculture have KMC strategies that are working. KM strategy developed by DAES is yet to be operationalized due to resources. This can hinder KM work, especially when projects phase out.
- According to the Akosombo Integration Agenda, [4] there are 10 areas that define the KM for agricultural development agenda for Africa which are, knowledge partnership and knowledge agenda, knowledge inclusion programmes, knowledge awareness programmes, knowledge management excellence programmes, national knowledge hub and digitization, advanced knowledge processes, basic models and resources mobilization, fake news and quality information standards and knowledge infrastructure and centers. There is need to integrate these components in the KM implementation of SAPP.

From the above priority areas, the paper concludes that there is yet to be a knowledge agenda and partnership that is spearheaded nationally in Malawi. There have been efforts to include knowledge management in new programmes implemented by the Ministry of Agriculture and there is some level of knowledge awareness, but more could be achieved. There is a need for a national knowledge hub and digitization housed at DAES. There is also need for more investment in Knowledge Management infrastructure and assigning more resources to KM in agriculture.

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Does Training on Climate Smart Practices Influence Adoption of Climate Smart Agricultural Practices among Women Rice Farmers in Nigeria?

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Abstract

The impact of climate change on food security has been worsened by gender disparity in access and use of climate technologies. In this study, the effect of training on Climate Smart Practices (CSP) on the adoption of Climate Smart Agricultural Practices (CSAP) among women rice farmers was examined. Data of 228 women rice farmers were collected using mobile app kobocollecttoolbox. Data were analyzed using descriptive statistics and multivariate probit regression analysis. The results revealed that majority of the women were from male-headed household (63.88%), married (65.35%) with at least primary education (77.19%) and an average age and household size of 41.14±10.86years and 8±4 persons, respectively. The women cultivated an average of 1.90±1.2 acres of land with farming experience of 14.83±11.47years. Majority of the women farmers had access to extension services (89.47%) while about 42% of the women farmers undergo training on CSP. Higher percentage of women farmers trained on CSP adopted good agronomic practices (83.16%); flooding/bunding/erosion control (73.68%); smart weather reader (54.74%) while lower percentage of the trained women farmers adopted solar drying technologies/equipments (10.53%) and biogas technologies/equipment (12.63%). The result of the multivariate probit regression showed that training on CSP increase the adoption of flooding/bunding/erosion control; smart weather reader; good agronomic practices; biogas technologies/equipment and solar drying technologies/equipments by 46.53%, 42.08%, 32.60%, 8.26% and 6.99% respectively. It is therefore recommended that training on enterprise specific climate smart practices should be organized and encouraged to speed up the rate of adoption of CSAP among women farmers.

Keywords: Climate Smart Practices; Training; Rice Production; Women Farmers.

Introduction

Agriculture is an important economic sector in Nigeria that contributes about 40% to the GDP and employed around 70% of the population (Olorunfemi *et al.*, 2020).In Nigeria, rice (*Oryza sativa L.*) is a vital staple food crop consumed by majority of the populace (PwC, 2017). The country is the highest rice-producing nation in Africa with production of about 8.3metric tonnes in 2021 compared to 4.8 million and 4.4 million metric tonnes produced by Egypt and Madagascar same year (Sasu, 2024). About 80% of rice in Nigeria are producedby small-scale local farmers while the remaining20% are produced by commercial farmers (PwC, 2017). Women farmers play a prominent role in food production around the world and in Nigeria women accounted for 75% of farming population (FMARD, 2013). Women farmers own one-tenth to one-fifth of global agricultural land (Shahbaz *et al*, 2022; WEF, 2017; FAO, 2014). Their share of food production is more than 50% worldwide (Swinbank, 2021; Ishaq and Memon, 2016) with 36.7% and 43.6% of women constituting the agricultural labor force in developed and developing countries respectively (Shahbaz *et al*, 2022; Luqman *et al.*, 2006). Thus, women farmers have a pivotal role in ensuring global food security and the rural development of developing countries (Asadullah and Kambhampati, 2021). Despite their enormous role in food production and agricultural growth, women farmers are confronted with tenacious social hindrances and economic restraints, for instance women farmers are disadvantaged in accessing productive resources and financial capital relative to their male counterpart (IFPRI, 2021; Meinzen-Dick *et al.,* 2019; Achandi *et al.*, 2018; Kieran *et al.,* 2017).

Agriculture in Africa mainly hinges on environmental factors and any prolonged variations in average weather conditions can have significant impacts on production. The sector is also characterized by land tenure insecurity, poor soil fertility, degraded ecosystems and climate variability (USAID, 2016). Agricultural production in Nigeria is mostly rain-fed and climate change is a severe challenge to rice farmers due to the sensitivity of rice to changing climatic conditions (Onyeneke, 2020; Tarfa *et al.,* 2019).Rice production's sustainability is greatly affected by climate change because it modifies economic opportunities, increases rice prices for consumers and reduces land areas cultivated by smallholder farmers thus resulting to smallholder farmers inability to match their outputs with inputs costs and agricultural technologiesas well as increased vulnerability to climate change (Sachin *et al.*, 2019; Baronchelli and Ricciuti, 2018). Climate change is a critical environmental issue that continues to threaten sustainable agricultural production and food security in Nigeria (Daba, 2018; Elijah Samuel *et al.*, 2018). Khatri-Chhetri *et al.* (2020) asserted that female farmers are more likely to be affected by climate impacts than their male counterpart especially in developing countries where their involvement in agriculture is high.

In 2010, the concept of Climate Smart Agriculture (CSA) came into limelight and the concept is defined as a form of agriculture that increases agricultural production and income; enhances adaptation and build resilience to climate change impact. CSA also helps to reduce the emissions due to Greenhouse gases (GHGs) and enhances the attainment of global food safety (FAO, 2014; World Bank, 2010). According to Olorunfemi *et al.* (2019) and Ojoko *et al.* (2017), climate-smart agricultural practices include activities that would ensure minimum tillage; application of organic agricultural practices rather than inorganic methods that would further deplete the soil in the long term; crop rotation and mulching to reduce evapo-transpiration; composting and planting of legumes and cover crops which assist in moderating the long-term effects of climate change by giving an enduring environmental strength to the soil. Improving rice farmers' welfare in rural communities and reducing their vulnerability to climate change impacts using adaptation measures aimed at sustainable increase in productivity, resilience to climatic risk and reduction greenhouse gas emissions are known as climate-smart agricultural (CSA) technologies, practices and services (Kurgat *et al.,* 2020; Khatri-Chhetri *et al.,* 2017).

Despite the potential benefits of climate-smart agricultural technologies, farmers' adoption rate is low in many developing countries (Amadu *et al.*, 2020; Kurgat *et al.,* 2020; Brown *et al.,* 2018) due to socio-economic factors, institutions, resource tenure, landscape governance, ecological and climatic conditions, the biophysical environment of a particular community, and the technology's attributes (Khatri-Chhetri *et al.,* 2017; Scherr *et al.,* 2012).Twyman (2014) explained that the adoption of CSA at the farm is not gender neutral, and there is need to understand the role of gender in CSA adoption on farms. Aryal *et al.* (2014) opined that female farmers are likelier to adopt CSA practices than males on their farms. Sraboni *et al.* (2014) further explained that women farmers' limited access and control over physical and human capital affect their livelihood and capacity to adopt different CSA practices at the farm level. Murray *et al.* (2016) reported that if women are giving more control of productive resources and decisional power regarding the management of the farm, there would be improvement in the adoption of CSA adoption on their farms. Oyawole *et al.* (2020) also asserted that households where women are more empowered tend to be more open to adopting new CSA practices.This implied thathigh rate of adoption of CSA by women farmers can be influenced by several factors in which the role of socio-economic and demographic characteristics such as age, household size, education which can be formal and informal training cannot be over emphasized.

Dlangalala and Mudhara (2020) explained that formal and informal training play essential role in technology adoption as it provides farmers with the required technical skills needed to carry out various activities on their farms.Informal training from climate change expert, extension agents and other relevant stakeholders would empower women farmers with the knowledge and skills needed to adopt CSA practices and this would result to increased crop resilience against adverse climatic conditions. The adoption of CSA practices among women farmers can increase rice yields thus contributing to local and national food security. Also the provision of training specifically tailored for women farmers would address the gender gap in agricultural knowledge and technology adoption thus fostering greater gender equity in farming communities. Therefore, the adoption of CSA practices to minimize climate impacts can be enhanced through informal training. From the aforementioned; the broad objective of the study was to examine the influence of CSA training on the adoption of CSA practices among women rice farmers in Nigeria. Specifically, the objectives were to;

i. identify the types of CSA training received by the women farmers
ii. describe the CSA practices adopted by the women rice farmers
iii. analyse the effect of CSAtraining on the adoption of CSA practices among women rice farmers.

Methodology

Study Area: The study was carried out in Nigeria.About 53% of the 213million Nigerians lived in urban areas. The country is made up of 101,575,770 rural populations in 2022 with 0.73% increase compared to rural population of 100,840,661 in 2021 (Macrotrends, 2024). The country is mainly an agrarian society characterized by three distinct climates zones namely monsoon climate in the south, tropical savannah climate for most of the central regions and a sahelian hot and semi-arid climate in the north of the country(World Bank, 2021). The country has a mean annual temperature of 26.9^{0}C and average monthly temperature ranging between 24^{0}C and 30^{0}C between 1991-2020. The country experienced highest temperature during the dry season and the mean annual precipitation in the country is 1,165mm. The country experienced rainfall throughout the year with most significant rainfall occurring from April to October. The relative humidity in Nigeria decreases from the South to the North with an annual mean of 88% around Lagos (World Bank, 2021). The country is made up of six geopolitical zones namely North Central, North East, North West, South West, South East and South-South.

Sampling Technique and Method of Data Collection

The data collected for the study was collected using mobile app KoboCollectToolBox. The instrument for the survey was deployed into the application and farmers were interviewed using mobile phones and tablets. Multistage sampling technique was used to select women rice farmers used in the study. In the first stage, four geopolitical zones were randomly selected out of the six geopolitical zones in the country. The selected zones were North Central, North East, South East and South West. Two states were randomly selected in the North Central while one state each was randomly selected in the three other geopolitical zones. The five states randomly selected were Ogun (South West), Enugu (South East), Taraba (North East) and Nasarawa and Kogi (North Central). Two local governments prominent for rice production in each of the five states were purposively selected and 25 women rice farmers were randomly selected in each local government. A total of fifty women rice farmers were randomly selected in each state making a total of 250 women rice farmers. At least 40% of the selected women farmers in each state undergo training on CSA practices. Out of the data of the 250 women rice farmers collected, only data of 228 women rice farmers were found analyzable.

Method of Data Analysis

Descriptive Statistics: Descriptive statistics such as frequency, mean and standard deviation, figures and charts were used to describe the socio-economic and farm enterprise characteristics of the rice women farmers and their households. It was used to assess the types of training received as well as the adoption of CSA practices among the women farmers.

Multivariate Probit Model:Multivariate probit was used to examine the influence of CSA training on adoption of CSA practices among rice women farmers. Multivariate probit is a generalization of the binary probit model. The analysis of decision on employment choice needs the use multivariate modeling framework in order to account for multiple employment types and the possible simultaneity of the decision-making process. In the Multivariate Probit model (MVP), the choice of employment relates to each type of employments correspond to a binary choice (Yes/No) equation whose choices are modeled jointly while accounting for the correlation among disturbances. The multivariate specification supersedes the univariate specification when the error correlations are significantly different from zero otherwise the two-modeling framework would lead to comparable results. Therefore, if there are three different employment types in rural areas. Three equations describing a latent dependent variable which corresponds which corresponds to the observed binary outcome for each type of employment would be needed to be estimated simultaneously.For the purpose of this study, a system of simultaneous probit was constructed for the five types of CSA practices identified following Cappellari and Jenkins (2003). These CSA practices are good agronomic practices, flooding/bunding/erosion control, smart weather reader, solar drying technologies/equipments and biogas technologies/equipments. The model is thus specified as:

$$Y^*_{ini} = \beta'_n X_{in} + \varepsilon_{in} \quad \text{...} (1)$$

$$Y^*_{ini} = 1 \text{ if } Y^*_{ini} > 0 \text{ and 0 otherwise}$$

N=1, ..., n ; ε_{in} are error terms distributed as multivariate normal each with a mean of zero and variance-covariance matrix V, where V has values of 1 on the leading diagonal and correlations $\rho jk = \rho kj$ as off-diagonal elements. If it is assumed that ε_{in} are distributed independently and identically with a univariate normal distribution, equation (1) defines N univariate probit models. The assumption of interdependence of the error terms implies that information about a farmer choice of CSA practice does not affect the prediction of the same woman probability of choice of another CSA practice. Although the whole set of N equations in equation (3) can be estimated separately by ignoring unobserved correlation among outcome but neglecting correlation would give inefficient and biased estimates.

In this study, the dependents variables in the MVP model include three dummy variables corresponding to the types of employment considered that is:

Y_1= Farmer adopts good agronomic practices (1 if yes, 0 otherwise)

Y_2= Farmer adopts flooding/bunding/erosion control (1 if yes, 0 otherwise)

Y_3= Farmer adopts smart weather reader (1 if yes, 0 otherwise)

Y_4= Farmer adopts solar drying technologies/equipments(1 if yes, 0 otherwise)

Y_5= Farmer adopts biogas technologies/equipments (1 if yes, 0 otherwise)

Note that these dependent variables were the same for all the five models

The independent variables are the Xs which are:

$X_{1=}$ Age of the farmer in years; X_2=Marital status of farmer (1 if farmer is married, 0 otherwise); X_3 = Education of farmer (1 if farmer is educated, 0 otherwise); X_4=Household size (number of persons); X_5=Sex of the household head (1 if male, 0 otherwise); X_6= Access to extension (1 if yes, 0 otherwise); X_7= Received CSA training (1 if yes, 0 otherwise); X_8=Log of income from rice production (Naira); X_9=Farming experience (in years); X_{10} = Area of land cultivated (Acres)

Result and Discussions

Socio-Economics and Farm Enterprise Characteristics of Women Rice Farmers

The socio-economic and farm enterprise characteristics of the women rice farmers were presented in Table 1. Majority of the women farmers were from male headed households (63.88%) with an average age of 41.13±10.86years. This implied that majority of women were still in their productive age and would be capable to carry out and monitor the various activities in rice production. This finding agreed with the result of Ojo *et al.* (2023). Higher percentage of the women farmers were married (65.35%) with at least primary education (77.19%). Educated and married farmers were likely to be committed to the output and yield of their production activities due to their knowledge and exposure as well financial commitment needed to fulfill family obligations. This finding is in line with the report of Girei *et al.* (2018) and Akintayo *et al.* (2024). Majority of the women farmers had 6-10 members of household with an average household size of 8±4persons. The large number of household members would serve as an indication of labour availability to the farmers especially in areas where there is scarcity of labour and lack of financial capability for the farmer to hire labour. This result tallies with findings of Michael (2022). Almost 90% of women farmers had access to extension with an average of 14.47±11.47years of farming experience. More years of experience denoted high endowment of human capital that would enhance efficient allocation and utilization of resources as well as ability to perceive and respond to various conditions such as economic and climatic condition that can affect rice production. This result was supported by the report of Ojo and Baiyegunhi (2023). Over 80% of women farmers cultivated less than or equal to 2acres of land and almost half of the women realized less than or equal to 200,000 naira from rice production. Agricultural production in Nigeria had been characterized with subsistence nature handled by resource poor farmers who produce over 90% of food consumed on small dispersed land holdings. This result corroborated with the report of UNCTA (2015).

Table 1: Socio-Economic and Farm Enterprise Characteristics of Women Rice Farmers

Variable	Participants (N=95)		Non-Participants (N=133)		Pooled (N=228)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Sex of Household Head						
Male	60	63.16	85	63.91	145	63.88
Female	35	36.84	48	36.09	82	36.12
Age of Farmers (years)						
<=35	38	40.00	44	33.08	82	35.96
36-45	32	33.68	38	28.57	70	30.70
46-55	19	20.00	33	24.81	52	22.81
>55	6	6.32	18	13.53	24	10.53
Mean	39.88±10.68		42.03±10.94		41.13±10.86	
Marital status						
Single	7	7.37	10	7.52	17	7.46
Married	63	66.32	86	64.66	149	65.35
Divorced /Widowed/Separated	25	26.32	37	27.82	62	27.19
Educational status						
No formal education	13	13.68	39	29.32	52	22.81
Primary education	29	30.53	54	40.60	83	36.40
Secondary education	29	30.52	21	15.79	50	21.91
Tertiary education	24	25.26	19	14.29	43	18.86
Household size (persons)						
1-5	27	28.42	37	27.82	64	28.07
6-10	51	53.68	87	65.41	138	60.53
11-15	13	13.68	9	6.77	22	9.65
>15	4	4.21	0	0	4	1.75
Mean	8±6		7±3		8±4	
Access to Extension Services						
No	3	3.16	21	15.79	24	10.53
Yes	92	96.84	112	84.21	204	89.47

Source: Data Analysis, 2024

Table 1b: Socio-Economic and Farm Enterprise Characteristics of Women Rice Farmers Cont'd

Variable	Participants (N=95)		Non-Participants (N=133)		Pooled (N=228)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Years of Experience in Rice Farming						
1-5	34	35.79	25	18.80	59	25.88
6-10	18	18.95	34	25.56	52	22.81
11-15	14	14.74	16	12.03	30	13.16
>15	29	30.53	58	43.61	87	38.16
Mean	13.20±10.86		16.34±11.53		14.47±11.47	
Land Cultivated in Acres						
<=2	86	90.53	109	81.95	195	85.53
3-5	8	8.43	20	15.04	28	12.28
>5	1	1.05	4	3.01	5	2.19
Mean	1.51±1.24		2.18±1.55		1.90±1.20	
Income from Rice Production						
<=200,000	52	54.74	61	45.86	113	49.56
200,001-300,000	15	15.79	19	14.29	34	14.91
300,001-400,000	11	11.58	11	8.27	22	9.65
>400,000	17	17.89	42	31.58	59	25.88
Mean	418,148.90±153,735.20		343,043.30±253,196.70		380,596.10±203,465.95	

Source: Data Analysis, 2024

Types of Climate Smart Agricultural Practices Training Received by Women Rice Farmers

The types of Climate Smart Agricultural Practices training received by the trained women rice farmers were presented in Figure 1. All the trained women farmers received CSA training on good agronomic practices, flooding/bunding/erosion control, use of smart weather reader, use of solar drying equipments/technologies and use of biogas technologies /equipments. Previous authors have explained the role of the various types of CSA trainings received by the women farmers on sustainable rice production. Hadi *et al.*(2022) opined that the use of agronomic solutions (such as different techniques of land preparation, choice of rice variety, crop establishment procedures, efficient water, weed and fertilizer management etc) would not only adapt rice production systems to changing climatic conditions but also reduce the negative environmental impacts on sustainable rice production. Onyeneke *et al.*

(2021) explained that flooding/bunding/erosion control is highly necessary in rice production as extreme climate effect such as flood has negative impact on rice crops due to erosion of top soils and nutrients flow off that can result to poor crop development and hinder the overall growth of the planted crop.

Bella *et al.* (2023) asserted that smart weather reader station would not only collect and analyze weather data but also provide real time weather information that would help farmers to reduce the impact of climate change on their production and business activities. Rizalman *et al.* (2023) opinedthat solar drying technologies to combat weather uncertainties such as rain and cloudy days during post-harvest period is highly necessary as utilization of solar powered drying technologies/equipments is not only beneficial economically compared to electricity powered drying equipments but also extend the shelf life and nutrient quality of agricultural products. In addition, Sahil *et al.* (2023) reported that rice straw is a rich lignocellulosic biomass that can be employed for biogas generation through digestion and this can serve as sustainable energy resources and prevent the underutilization of the bye-product as well as prevent health and environmental hazards associated with the burning of rice straw. This implied the types of training received by the women farmers are highly relevant toward mitigation of the impact of climate change on rice productivity and sustainable rice production in Nigeria.

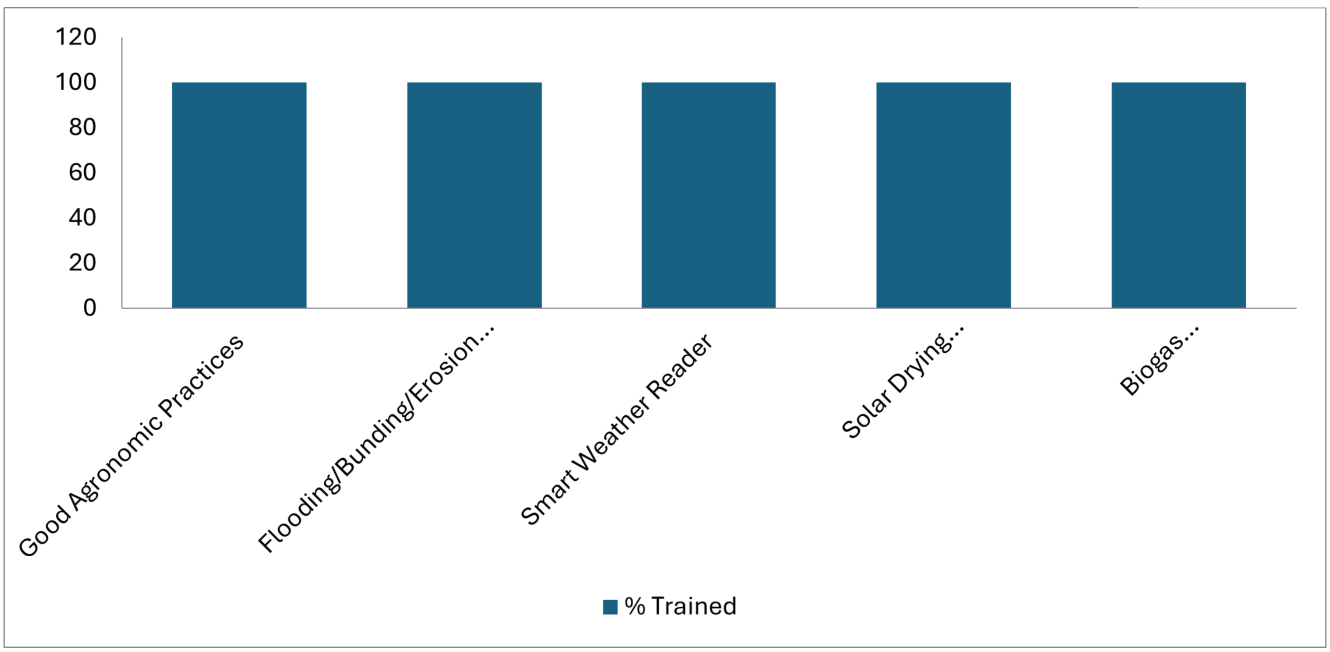

Figure 1: Types of Climate Smart Agricultural Practices Training Received by Trained Women RiceFarmers

Adoption of Climate Smart Agricultural Practices among Trained Women Rice Farmers

The adoption of climate smart agricultural practices among the trained women rice farmers was presented in Figure 2. Over 80% of the women farmers adopted good agronomic practices. Almost 74% of the women farmers adopted flooding/bunding/erosion control while about 55% of the women farmers adopted smart weather reader. It was further revealed about 11% and 13% of the women farmers adopted the use solar drying technologies/equipments and biogas technologies/equipments respectively. Saran and Puskur (2023) affirmed that knowledge dissemination approaches targeting women increase their use of climate-smart agricultural practices as targeted efforts/programmes to enhance women's awareness and knowledge about CSA practices and their benefits are effective at increasing their adoption of CSA practices. The most adopted CSA practice was good agronomic practices while the least adopted CSA practice was the use of solar drying technologies/equipments. This result agrees with the findings of Ojo *et al.* (2023) who reported that rice farmers in Osun State Nigeria mostly adopted

CSA that are knowledge smart and least adopted CSA that are energy smart.

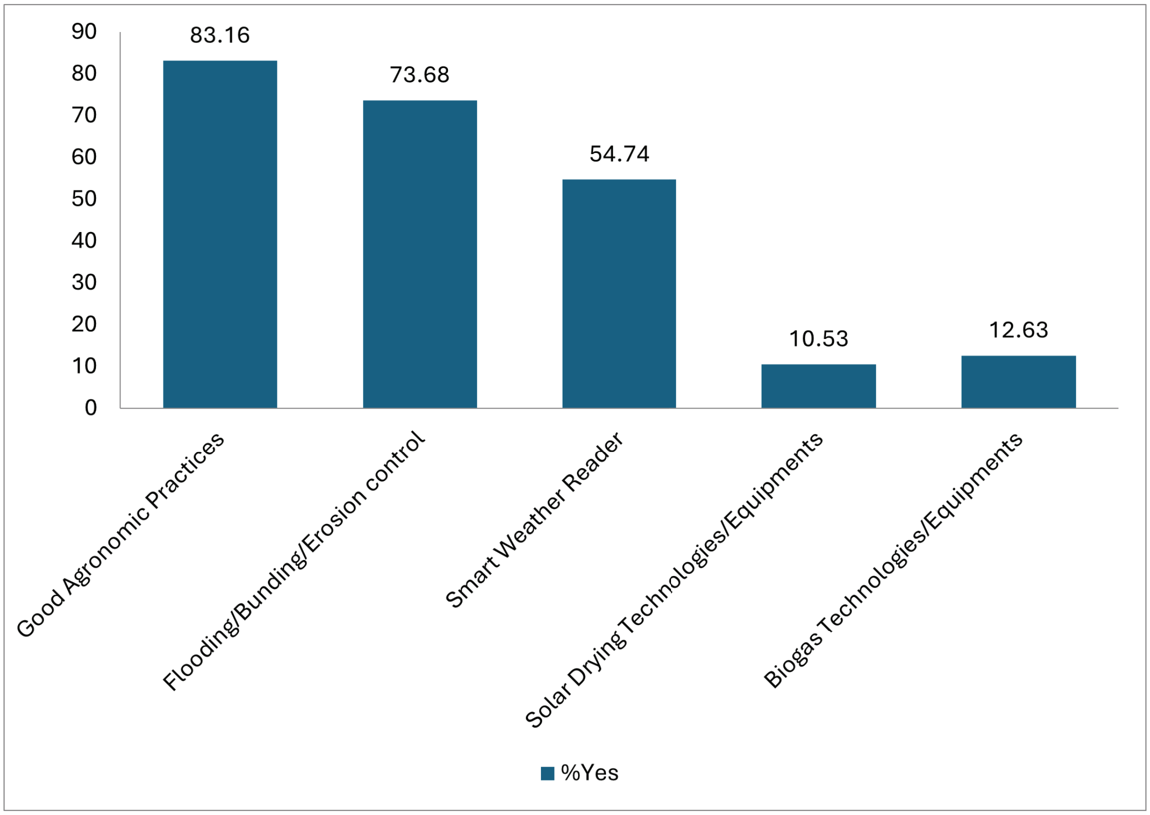

Figure 2: Adoption of Climate Smart Agricultural Practices among Trained Women Rice Farmers

Influence of CSA Training on Adoption of CSA Practices among Women Rice Farmers

The influence of CSA training on adoption of CSA practices among women rice farmers was presented in Table 2. The coefficient of training was positive and significant for all the CSA practices that the farmers received training at varied magnitude. The coefficient of participant received training was positive and significant at 1% for good agronomic practices. This implied that participation in training on CSA increased the probability of adoption of good agronomic practices by 32.59%. Sennuga *et al.* (2020) attributed high level of adoption and acceptance of good agricultural practices to training of farmers in Nigeria. The coefficient of participant received training was positive and significant at 1% for flooding/bunding/erosion control. This implied that participation in training on CSA increased the probability of adoption of flooding/bunding/erosion control by 46.53%. The coefficient of participant received training was positive and significant at 1% for smart weather reader.This implied that participation in training on CSA increased the probability of adoption of smart weather reader by 42.08%. The coefficient of participant received training was positive and significant at 5% for solar drying technologies/equipments. This implied that participation in training on CSA increased the probability of adoption of solar drying technologies/equipments by 6.99%. The coefficient of participant received training was positive and significant at 1% for biogas technologies/equipments. This implied that participation in training on CSA increased the probability of adoption of biogas drying technologies/equipments by 8.26%. These findings had been previous affirmed by Saran and Puskur (2023).

Influence of Socio-economic Variables on Adoption of CSA Practices among Women Rice Farmers

Besides participation of the women farmers in CSA training, other socio-economic variables that influenced adoption of CSA practices revealed in Table 2 were age of farmer, education of farmer, household size and income from rice production.The coefficient of age of farmers was negative and significant at 5% for adoption of solar drying technologies and equipments. This implied that younger women farmers were more likely to adopt solar drying equipments and technologies than older women farmers. This is not surprising as younger people are high risk takers that are always eager to try new innovations. This finding was supported by the reports of Jack *et al.* (2022); Bianchi *et al.* (2022) and Saadu *et al.* (2024). The coefficient of education was negative and significant at 5% for good agronomic practices. This implied that women farmers with no education were more likely to adopt good agronomic practices. This may be due to the fact knowledge of good agronomic practices may not require through formal education as they can be acquired through seminars, workshops and other training outlet organized by farmer's group, extension agents among others. This result is contrary to the finding of Sennuga and Fadiji (2020).

The coefficient of household size was positive and significant for smart weather reader, solar drying equipments/technologies and biogas equipments/technologies at 5% and 10%. This implied that households with more members were more likely to adoptsmart weather reader, solar drying equipments/technologies and biogas equipments/technologies. A unit increases in household size increase the probability of adoption smart weather reader, solar drying equipments/technologies and biogas equipments/technologies by 1.16%, 0.70% and 1.09% respectively. Households with more members would likely use energy smart CSA solutions to reduce the impact of climate change so that the sustenance of the household would be guaranteed. This finding is supported by the result of Muriithi *et al.* (2021). The coefficient of income from rice farming was positive and significant for adoption of flooding/bunding/erosion control at 5%. This implied that women farmers with increased income from rice production were more likely to adopt flooding/bunding/erosion control. This may be due to the financial implications that are associated with controlling for erosion and flooding especially in areas that are prone to flooding and erosion. Saadu *et al.* (2024) agreed that farmers that adopted climate smart agricultural practices were more likely to have increased income therefore more income from agricultural production enhance adoption and adoption would also result to mitigating impact of climate change and more income for farmers.

Table 3: MultivariateProbit Regression Result showing the Influence of CSA Training on Adoption of CSA Practices among Women Rice Farmers

Variables	Climate Smart Agricultural Practices				
	Good Agronomic Practices	Flooding/Bunding/ Erosion control	Smart Weather Reader	Solar Drying Technologies/ Equipments	Biogas Technologies/ Equipments
Age of Farmer	-0.0021	0.0026	-0.0019	-0.0037**	-0.0019
	(0.0036)	(0.0035)	(0.0032)	(0.0019)	(0.0018)
Marital Status	0.0587	-0.0457	0.0109	-0.0107	-0.0495
	(0.0865)	(0.0845)	(0.0764)	(0.0446)	(0.0442)
Education	-0.1844**	0.0131	0.0568	0.00504	0.0069
	(0.0781)	(0.0763)	(0.0690)	(0.0403)	(0.0399)
Household Size	-0.0055	0.0019	0.0116*	0.0068*	0.0109***
	(0.0071)	(0.0069)	(0.0063)	(0.0036)	(0.0036)
Sex of Household Head	0.1201	0.0478	0.0155	-0.0726	-0.0028
	(0.0886)	(0.0866)	(0.0783)	(0.0457)	(0.0452)
Access to Extension	-0.0077	-0.0970	0.0303	-0.1342	-0.0202
	(0.1015)	(0.0992)	(0.0897)	(0.0524)	(0.0518)
Received CSP Training	0.3259***	0.4653***	0.4208***	0.0699**	0.0826***
	(0.0641)	(0.0626)	(0.0567)	(0.0331)	(0.0327)
Income from Rice Prod	0.0363	0.0693**	0.0410	0.0020	0.0013
	(0.3518)	(0.0344)	(0.0311)	(0.0181)	(0.0179)
Farming Experience	0.0026	-0.0053	0.0031	0.0008	-0.0011
	(0.0034)	(0.0034)	(0.0030)	(0.0018)	(0.0017)
Acres of Land Cultivated	-0.0070	-0.0052	-0.0013	0.0005	0.0002
	(0.0069)	(0.0068)	(0.0062)	(0.0036)	(0.0036)
Constant	1.8485***	1.7412***	1.0032**	1.2697***	1.0089***
	(0.5331)	(0.5208)	(0.4713)	(0.2750)	(0.2721)

*Source: Data Analysis, 2024; ***, **, * denote Significant at 1%, 5% and 10%.*

Conclusion and Recommendations

The study examined the influence of training on CSA on adoption of CSA practices among rice farmers in Nigeria. Data of Data of 228 women rice farmers were collected using mobile app kobocollecttoolbox. Data were analyzed using descriptive statistics and multivariate probit regression analysis. The results revealed that majority of the women were from male-headed household (63.88%), married (65.35%) with atleast primary education (77.19%) and an average age and household size of 41.14±10.86years and 8±4 persons, respectively. The women cultivated an average of 1.90±1.2 acres of land with farming experience of 14.83±11.47years. Majority of the women farmers had access to extension services (89.47%) while about 42% of the women farmers undergo training on CSP. Higher percentage of women farmers trained on CSP adopted good agronomic practices (83.16%); flooding/bunding/erosion control (73.68%); smart weather reader (54.74%) while lower percentage of the trained women farmers adopted solar drying technologies/equipments (10.53%) and biogas technologies/equipment (12.63%). The result of the multivariate probit regression showed that training on CSP increase the adoption of flooding/bunding/erosion control; smart weather reader; good agronomic practices; biogas technologies/equipment and solar drying technologies/equipments by 46.53%, 42.08%, 32.60%, 8.26% and 6.99% respectively. Other socio-economic variables that influenced adoption of CSA practices revealed in the study were age of farmer, education of farmer, household size and income from rice production. The study thus recommends that training on enterprise specific climate smart agricultural practices should be organized and encouraged to speed up the rate of adoption of CSA practices among women farmers. Women farmers that benefitted from such training should be encouraged to step down the training to other farmers in their locality/communities in order to speed up the rate of adoption, mitigate negative impact of climate change and ensure food security and sustainable livelihood are guaranteed.

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Parallel Session 4

Theme: Governance Issues in CSA and Food System Transition

Boosting Crop Yields in Southwest Nigeria: The Role of Social Networks and Fertilizer Use among Smallholder Farmers.

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Abstract

The role of fertilizer in the sustenance of agricultural productivity growth in many developing countries is enormous. Despite this, level of fertilizer usage in small-scale agricultural production in Nigeria is generally low. This can however be improved upon through enhanced access to social capital. Therefore, this study investigates the levels of social capital and fertilizer usage in crop production among small-scale farming households in south-west Nigeria. A four-stage random sampling technique was employed in collecting primary data from 352 farming households in Oyo State. The data were analyzed using descriptive statistics, Principal Components Analysis (PCA), Multinomial Logit regression, Tobit regression, Production Function and student t-test. The alpha level for the test of significance is at 5 per cent.

The findings of the study were that: There was high participation (64%) in agricultural groups and that farming households belong to three levels of social capital comprising bonding (25%), bridging (12%) and linking (63%); the probability of farming household having bonding social capital relative to bridging social capital increases with sex of the head of household and position held in group, but reduces with age of household head; the tendency of having linking social capital among farming households relative to bridging increases with farm size and amount of credit received by the household as well as age, sex, and level of education of the household head ; majority (85%) of the households used fertilizer at an average application rate of 120.74kg/ha; intensity of fertilizer usage increases with increased social capital indices such as heterogeneity index and decision making index; and while crop production is affected by farm size, quantity of fertilizer, planting materials and hired labour, fertilizer application increased output by 62.87 percent.

The study concluded that social capital has a positive impact on fertilizer usage and crop output in the study area and that, its level is influenced by the socioeconomic characteristics of the farming households. The study recommended that agricultural groups need to be strengthened and supported by the government and the community through services in the area of input supply, such as fertilizer, provision of credit facilities and direct purchase of farm produce. Farmers should also be enlightened and given proper orientation by extension agents through training on proper fertilizer application.

Keywords: Fertilizer, Social capital, Intensity, Principal Components Analysis (PCA),

Introduction

Agricultural productivity growth in sub-Saharan Africa lags behind that of other regions in the world; well below the level which is required to achieve food security and poverty reduction. In addition, many farmers in the region face declining crop yields, which have adverse effects on the region's economic growth (Akpan, Udoh & Nkata, 2012). In Nigeria, agricultural sector like in most other developing countries is dominated by small - scale farmers. This category of farmers produce about 80 percent of the total food (Oji-Okoro, 2011; Nations Encyclopedia, 2015) by cultivating between 0.8 to 1.2 hectares in forest area and 2 to 4 hectares in the savannah areas where land preparation is easier (Federal Fertilizer Department, FFD, 2011). Further, small-scale farmers as described by O.A. Omotesho (2015) are characterized by low asset base, low fixed capital investment, labour intensive practice, small farm size, low investment and expenditure on farm inputs and improved technologies, crude tools and equipment and low productivity, among others.

Furthermore, one major problem facing farmers in Africa and Nigeria in particular is the increasing population density and urbanization. This has resulted in land use intensification leading to the collapse of the traditional land fallow system of crop production, increased soil nutrients depletion and low crop yield among farmers (Azagaku & Anzaku, 2002). This is as a result of continuous cultivation without planned replenishment of depleted soil nutrients (Wanyama, Moses, Rono, Masinde & Serem, 2009). The depletion and degradation of land and water pose serious challenges to producing enough food and other agricultural products to sustain livelihoods in the rural areas and meet the need of the urban population (World Bank 2014). Therefore, adding nutrients to the soil is crucial to sustainable agriculture; as this would compensate for depletion of nutrients through crops grown.

In view of the above, restoring soil fertility levels is crucial to increasing agricultural productivity which has become a necessity in the sub-Saharan Africa, especially Nigeria.

One of the fundamental ways of improving agricultural productivity is through effective use of chemical fertilizer (hence forth, fertilizer). Ayinde, Adewumi and Omotosho (2009) rightly pointed out that Nigerian agriculture needs to embrace the use of fertilizer, improved seeds and crop protection products since the possibility for land expansion is limited in order to increase agricultural productivity. Fertilizer can therefore be said to be a powerful productivity enhancing input. It is in fact very crucial for crop production by small scale farmers. Increased use of mineral fertilizer has played an important role in many developing countries that have experienced high and sustained levels of agricultural productivity growth. Indeed, one-third of the increase in cereal production. worldwide has been attributed to fertilizer related factors (FAO, 2008). Increased consumption of chemical fertilizer in China's farming sector from an average of 169kg/ha to 390kg/ha contributed to the increase in the country's grain yields increase from 3.7 tons to 5.3 tons per hectare between 1983 and 2008 (Zhou, Yang, Mosler, & Abbaspour, 2010). Likewise, in India according to FAO statistics, 50 percent of the increase in India's grain production has also been attributed to fertilizer related factors. Therefore, the importance of fertilizer in crop production cannot be overemphasized.

However, agricultural sector in Oyo is hindered by many factors. According to Oyo State Ministry of Agriculture (2014), the factors include the average land holding and yield per hectare which is generally low due to inadequate supply of fertilizer and other farm inputs, as well as lack of access to micro-credit. Another major constraint facing the farming households in the state is high post harvest losses due to poor storage facilities.

When individuals share common interests and beliefs, communication among them is more likely to be effective. Therefore, information about use of fertilizer to increase crop output may in fact be more effective if shared through social interactions (Abdul, Munasib & Jefrey, 2011). Social capital, which generally refers to trust, social norms, and networks, has been widely recognized in literature in recent times to have positive consequences on economic and social development. It has become a critical issue in agricultural development as it plays a crucial role in collective actions, such as management of common resources and technology adoption. It is a set of supportive interpersonal interactions that exists in the family and community (Isreal, Beaulieu & Hartless, 2001). At the household level, social capital can be defined as the relationship between different family members that determines how an individual member can take advantage of whatever financial and human capital other family members possess (Martin, Rogers, Cook & Joseph, 2004). At the community level, social capital can be defined as having relational, material and political elements. Social capital consisting of social networks and associated norms have effect on the productivity of the rural community. It facilitates coordination and cooperation, for the mutual benefits of the members of the association. Social capital, as built through households and community involvement, may enhance social responsibility thereby promoting the use of sustainable agricultural farming practices including use of fertilizers: When individuals interact with one another, a transfer of information often takes place.

Indeed, social capital has been identified as one of the possible factors that could explain why development performance differs across nations or communities. Involvement in associations may also contribute to learning and training in sustainable agriculture practices. For instance, a farmer may learn new techniques and know-how, obtain informal training from others who have already adopted such practices, and even obtain help implementing various practices. Social capital is therefore crucial for increased crop production by promoting farmers' access to information about fertilizer and fertilizer usage as well as access to fertilizer. This is possible because social capital provides social networks, relationships and linkages that enable poor people to cooperate, coordinate, share information and resources, and act collectively. Different levels of social capital shape the decision to use and the extent of fertilizer usage. According to Njuki, Mapila, Zingore and Delve (2008), different levels of social capital influence the use of technologies differently. For example, technologies that are knowledge intensive may require different forms of social capital than those that are labour or input intensive.

This study considered three levels of social capital viz-a-viz bonding, bridging and linking from the perspective that a farming household member is influenced to use fertilizer to increase his/her crop yield because of the influence of a friend or other members of his/her household, group, groups outside the community and external links with collaborators like government, NGO, extension agents, international organizations and so on. Social capital is in fact the ties, networks and linkages between individuals, groups and communities that bind and bridge society.

Literature review

The different theories developed through reviews of previous studies with tested knowledge of the study variables as well as the specific theory to be adopted for this study are presented in this section. Which is the social capital theoretical framework. Social capital has become one of the key concepts in understanding relationships among farming households, socioeconomic characteristics as well as production activities, that is, performance of farming households. However, Social capital refers to network of social connections that exist between people, also refers to as shared values and norms of behaviour which enable and encourage mutually advantageous social cooperation among individuals. The different types of connections among the members of group characterise not only different types of relationships but also different types of structural dimensions of socialcapital. Three main dimensions of social capital (seen as levels of social capital in this study) have been identified in literature: bonding, bridging and linking social capital.

Bonding social capital which consists of strong ties within a horizontal network, including family, close friends, neighbours, colleagues and so on, it's a link to people based on a common identity. That is people who share culture or ethnicity. Bridging social capital on the other hand encompasses more distant ties of like persons, individuals sharing similar economic and political position but who differs in terms of location, occupation, or ethnic group. That is, this link stretches beyond a shared sense of identity. It includes distant friend, colleagues, and associates. Linking social capital implies vertical ties with formal institutions and organizations. The most common and popular approaches to measuring social capital are: census of groups and group memberships (Beugelsdiyk & van Schaik, 2005) in a given society, the use of survey data on level of trust (Fukuyama 2001), civic participation (Casey, 2004), and so on. Woolcock (1998) and Fukuyama (2001) argue that although trust and associational activity are used as social capital indicators, they might instead be one of its consequences rather than the social capital itself. Voluntary associations might be characterised by members that are relatively homogeneous in character (Sabatini, 2009). This high level of homogeneity within the group is likely to reduce new possible bridges between circles. The crucial missing element is that these indicators of social capital mentioned so far do not consider enough the structural dimensions of social capital. According to Uphoff 1999) the structural dimension of social capital refers to a variety of networks that contribute to cooperation and more specifically to mutually beneficial collective actions.Indeed, social networks can be considered as a powerful means to spread information and knowledge at lower transaction costs and uncertainty (Grootaert 2001; Sabatini, 2009). Hence, the structural dimensions of social capital become crucial in order to construct a "reliable" indicator. For "reliable" we mean a social capital indicator that satisfies the trust-cooperation complex of Paldam (2000). This particular concept indicates that trust and cooperation are two interlinked elements that any social capital indicator should be able to satisfy somehow and it can be expressed as follows:

'Trust → ease of voluntary cooperation ‡ e'

Where: e is a small error; the ease of voluntary cooperation indicates the ability of individuals to work together, which also corresponds to the definition of social capital provided by Coleman (1988); trust indicates the trust among the individuals involved in the process of cooperation. The trust-cooperation complex implies that the structural dimension of social capital play a fundamental role in the construction of the measure.

The structural dimensions of social capital recall the network analysis advanced by Granovetter (1995). Past research efforts have been on social capital in relation to household welfare such as that of Yusuf (2008), social capital and poverty such as Anyiro (2014) and social capital and access to micro credit like that of Balogun and Yusuf (2011) to mention a few. There is no empirical research work on the link between social capital and extent of fertilizer usage in literature.

Materials and Methods

The study was conducted in Oyo State Nigeria. Oyo State is bordered to the north by Kwara State for 337 km, to the southeast by Osun State for 187 km, partly across the River Osun, and to the south by Ogun State, and to the west by the Republic of Benin for 98 km. With a projected population of 7,976,100 in 2022, Oyo State is the sixth most populous in Nigeria.

Oyo State covers approximately an area of 28,454 square kilometers and is ranked 14th by size. The landscape consists of old hard rocks and dome shaped hills, which rise gently from about 500 meters in the southern part and reaching a height of about 1,200 metres above sea level in the northern part. The climate is equatorial, notably with dry and wet seasons with relatively high humidity. The dry season lasts from November to March while the wet season starts from April and ends in October. Average daily temperature ranges between 25 °C (77.0 °F) and 35 °C (95.0 °F), almost throughout the year. Primary data was obtain through the use of Surveybe. The sampling frame for this study consists of farmers growing arable crops in Oyo. This study adopted Three-stage random selection process and procedure was used for this study. The first stage was the purposive selection of Oyo state, the second stage was the random selection of one block from each ADP zone. In the third stage, three communities was selected randomly from each block, and the last stage was the random selection of arable farmers from each of the communities. The selections were made using the existing communities listings and list of farming households with the state ADP zones as the sampling frame. All the 352 questionnaires provided valuable information and hence were used for analysis.

Descriptive statistics such as a table, frequency, charts, Principal Component Analysis (PCA), Multinomial logit regression, production function analysis, Tobit regression model and t-test. the model was employed for the data analysis.

Principal component analysis (PCA) is a multivariate technique that analyzes a data table in which observations are described by several inter-correlated quantitative dependent variables.

The PC model can be specified mathematically following Brooks, Shoecraft and Franklin (2008); Anim and Mandleni (2010)

$$PC = W_1 y_1, + W_2\ y_2 + \ldots + W_{22}\ Y_2 \ldots\ldots\ldots (1)$$

Where, PC = principal components

y_1, y_2, y_{22}= original variables in the data set and W_1 –W_{22} = eigenvectors extracted from the covariance or correlation matrix of the data set. “Setting aside” the best combination (and label it PCI) and searching for the second-best, and the third-best, etc. up to the 3rd-best combination, give us a set of 3 component scores. Each of these scores maximizes the sum of squares correlations (with the y_1 –y_{22}) subject to it being uncorrelated to all of the previous scores.

$$PC_1 = W_{11}\ y_1 + W_{12}\ y_2 + \ldots + W_{122}\ y_{22} \ldots\ldots\ldots (2)$$

$$PC2 = W_{21}\ y_1 + W_{22}\ y_2 + \ldots + W_{222}\ y_{22} \ldots\ldots\ldots (3)$$

$$PC3 = W_{31}\ y_1 + W_{32}\ y_2 + \ldots + W_{322}\ y_{22} \ldots\ldots\ldots (4)$$

Only the principal components with eigen-values higher than unity were retained. The eigenvalue for a given factor measures the variance in all the variables which is accounted for by that factor. If a factor has a low eigenvalue, then it contributing little to the explanation of variance in the variables and may be ignored. (Anim & Mandleni, 2010)

Results and Discussion

The socioeconomic characteristics of the Farmers are presented in table1.The mean age of the household heads was 51.20 ÷ 9.49 years. Age has been identified as one of the factors that affect labour as well as farm productivity. It determines the quality and quantity of work a farmer can do and the ease with which agricultural innovations are accepted (Fatoba, 2007; Ojeleye, 2015). People tend to wear in energy as they advance in age and may no longer be capable of providing the type of efforts required by rudimentary farming. About 60 percent of the household heads are within the modal age group of 41 to 60 years. This result indicates that the household heads are tending towards old age and may imply decline in labour productivity with time. This is in line with the findings of Fatoba (2007) who found 46 percent of fadama rice farmers to be about 50 years of age and in contrast to Anyiro (2014) who found mean age of farm households to be 40.79 years.

Minimum age recorded was 35 years while maximum was 75 years. Only about 20 percent of the households are less than 40 years of age. The Nigerian National Youth policy (2009) defines youth as adult between the age of 18 and 35 years. This result may clearly indicate that youths participate less in agricultural groups as well as crop farming in the study area. This probably is because youth in the study area want easy and quick money so they are more engaged in motorcycle riding than farming. Only a small proportion of the farming household heads had no formal education” (13%). The rest had one form of education or the other ranging from primary to tertiary. This enhances their access to and usage of fertilizer as well as credit facilities and extension messages. This finding is in conformity with that of Ojeleye (2015) who found 10percent of crop farmers in Kaduna State having no formal education. Also in line with the findings of K.F. Omotesho (2015) who also found higher proportion (68%) of crop farmers in both Kwara and Oyo States of Nigeria to possess one form of formal education or the other.

This study finds marital status distribution of the farming households in general to be skewed. Majority (81%) are married while only 19 percent are not married. For the purpose of this study, other categories of marital status such as divorced and widowed were classified as not married. Household size was adjusted by estimating the adult-male equivalent. An approximate value of 7 ÷ 2.98 was obtained as mean household size for the entire study area with a minimum of 1 and a maximum of 16. A majority (61%) had 5-8 members per household. About 72 percent of the household heads had between 21 and 40 years of experience in farming. The minimum year of experience was 5 while the maximum was 52 years. The result further shows an average of 23 + 10.79 years of farming experience. It is expected that with increasing years of farming, farming households would gain more experience in the art of farming leading to increased crop productivity.

Farming Households Participation in Agricultural Groups

Table 3 presents the distribution of agricultural group membership among farming households. A substantial majority (64%) of households participated in at least one agricultural group, while 36% had no affiliations. Government-funded groups, such as FUG, NPFFS, and RTEP, were the most common (40%) among participating households. Other forms of membership included agricultural-based mutual support groups (e.g., Cassava Growers Association) and agricultural cooperatives. Additionally, 16% of households had members involved in groups outside their community. Membership in agricultural groups provided significant advantages, particularly in accessing government and financial resources. Survey findings indicated that many government programs and bank credits were exclusively available to members of registered agricultural groups. For instance, a state government, in collaboration with the Bank of Agriculture, offered N100,000 credit to individual farmers, but disbursement was restricted to group members.

On average, farming households with group memberships had two members involved in these organizations. While 39% of households had one or two members participating, only 6% had more than four members in agricultural groups.

Effect of Fertilizer Usage on Crop Output in the Study Area

Table 5 shows major crop outputs distribution by fertilizer usage. To show the effect of fertilizer usage on crop production, the output of some major crops were compared between users and non-users of fertilizer. The average farm size for users and non-users of fertilizer was about 2.80 ha and 2.41 ha, respectively. The farm size of fertilizer users was lowest for sorghum (2.57 ha) and highest for cassava (3.21ha), while the non users have highest for yam (2.9 ha) and lowest for sorghum (1.16 ha). Generally, the farm size for users of fertilizer was higher than for non-users except for yam where users had a mean of 2.69 and non-users 2.9 ha under cultivation. The output level was also generally higher for fertilizer users than non-users. This result may be attributed to the usage of fertilizer. In consonance with a priori being equal. The result of the t-test also confirms this. The t-test value of 8.35 revealed a significant difference in the level of output of users of fertilizer and non-user farming households with much variability. The mean output of fertilizer users and non-users was 13201.1-grain equivalent and 4901.58-grain equivalent respectively. Output of fertilizer users was therefore higher than that of non- users by 62.87 percent. This result is in conformity with that of Mohammed (2014) who found crop output of households with low malaria incidence to be 75 percent higher than those with high malaria incidence in Kwara.

Conclusion and Recommendation

Agricultural groups have prospects for farming households in the form of social capital and provide the members with the opportunity of benefiting from the interplay of group dynamics which led to higher crop productivity. When farmers come together, they are able to pool their resources together for both individual member's economic empowerment and communal cohesion. They are quite often a contact point for extension services and form linkages even with government institutions responsible for agricultural development programme. Based on the empirical evidence emanating from both descriptive and inferential statistics employed for this study, it can be concluded that there is high potential of increasing crop output in the study area if farming households intensify the use of fertilizer. Social capital also has positive influence on fertilizer usage, indicating that there is a link between social capital, fertilizer usage and crop output in the area. Level of social capital is as well influenced by the socioeconomic characteristics of the farming households. Therefore, strengthening social capital would enhance fertilizer usage which will further be reflected in the increased productivity of crop farming in the study area

Based on the findings of the study, the study recommended that agricultural groups in the area should be supported and strengthened through support services like supply of inputs (such as fertilizer, other agrochemicals and improved varieties of planting material) at reduced price, provision of credit facilities, direct purchase of farm produce by government and community people themselves. This would encourage those who are not yet in groups to join, so that they can also possess social capital. There should be increased awareness about activities of agricultural groups by government and extension agent for non-members to develop interest in group membership. This could be achieved through broadcasting of group programmes on radio and jingles.

List of Tables

Table 1: Distribution of respondents' socio-economic characteristics.

Characteristics	Frequency	Mean	Std dev	n=352 Min	Max
Age of household head (years)					
≤ 40	70(19.89%)	51.2	±9.49	35	75
41-50	108(30.68%)				
51-60	102(28.98%)				
Above 60	72(20.45)				
Sex of Household head					
Male	320(90.91%)				
female	32(9.09%)				
Educational status	45(12.78%)				
No formal education	45(12.78%				
secondary	70(19.89%)				
tertiary	58(16.48%)				
Marital Status					
married	284(80.68%)				
Not married	64(19.32%)				
Adjusted household					
1-4	35(9.94%)				
5-8	213 (60.51%)	6.89	±2.98	1	16
9.12	73(20.74%)				
Above 12	31(8.81%)				
Farming experience					
≤ 10	5(1.42%)	23	±10.79	6	53
11-20	17(4.83%)				
21-30	124(35.23%)				
31-40	129(36.65%)				
41 and above	77(21.87%)				

Source: Author's Computation, 2024

Table 2: Summary of statistics on the indices of social capital

Social capital index(%)	means	Minimum	Maximum	SD
Density of membership	34.59	20	60	8.94
Heterogeneity index	42.67	7.14	71.43	13.94
Decision making index	64.9	0	80	34.13
Meeting attendance index	75.43	33.33	96.47	30.62
Cash contribution index	10.05	0	100	15.96
Labour contribution index	47.35	0	100	33.11

Source: Author's Computation, 2024

Table 3 Distribution of farming household according to contribution to groups

Group characteristics	Frequency	Percentage	Min	Max	Mean n=352
Types of contribution to group					
Not Applicable	128	36.36			
None	54	15.34			
Cash	134	38.07			
Kind	21	5.97			
Both	15	4.26			
Household member who contributed					
Not Applicable	128	36.36			
none	62	17.61			
1-2	88	25			
3-4	56	15.91			
above 4	18	5.11			
Amount of cash contributed					
Not Applicable	128	36.36			
≤ 50,000	156	44.32	500	300,000	64848±5602.98
51,000-100,000	29	8.23			
101,000-150,000	18	5.11			
151,000-200,000	10	2.84			
200000 and above	11	3.13			

Source: *Author's Computation, 2024*

Table 4: Principal components analysis of the social capital variables

Variables	Principal component PCs			
	linking PC1	bonging PC2	bridging PC3	ah
Cummulative Variance (%)	70.1	77.89	82.84	
Membership in group outside the community	-0.02	-0.11	0.67	89.33
Connection with corporate organization	0.63	0.35	0.54	81.84
Interaction with other groups	0.46	0.23	0.67	72.27
Kind of interaction	0.21	0.69	0.49	73.05
Type of corporate organization	0.64	0.34	0.55	82.44
Criteria for membership	0.74	0.54	0.19	87.54
Regularity of contribution	0.68	0.54	0.4	90.69
Extent of cooperation	0.55	0.72	0.27	89.35
Membership heterogeneity	0.5	0,78	0.23	90.3

Participation in decision	0.71	0.55	0.33	91.89
Regularity of meeting	0.2	0.8	0.09	69.41
Notice of absence	0.66	0.5	0.38	82.89
Fine payment	0.17	0.16	0.93	92.1
Adherence to norms	0.17	0.16	0.92	90.22
Willingness to confront members problem	0.69	0.55	0.39	93.97
Knowledge of procedures and norms	0.07	0.82	0.18	70.71
Frequency of lending possession	0.67	0.51	0.19	75.04
Extent of trusting others	0.64	0.48	0.38	79.15
Perception on other people helping	0.54	0.67	0.42	92.05
Extent of participation in group activities	0.12	0.91	0.15	85.71
Degree of volunteerism	0.71	0.54	0.36	91.76
Extent of financial contribution	0.52	0.26	0.64	75.15
percentage variance of each PC	70.1	7.8	4.95	
Eigenvalues	17.52	1.95	1.95	

Source: Author's Computation, 2024

Table 5 :Major crop distribution by farm size, crop output and fertilizer usage

	Fertilizer	**Users**	**n=298**	**Non-user of fertilizer**		**n=54**
Major crops	**farms size**	**yield**	**output grain equivalent**	**farm size(ha)**	**yield kg/ ha**	**output grain equivalent**
cassava						
mean	3.21	15376.49	6458.13	2.3	11113	4667.46
minimum	1.5	2500	1050	0.5	10000	420
maximum	7	150000	63000	3	70000	29400
Maize						
mean	2.78	3579.31	4080.41	2.38	2350	2679
minimum	1	218.2	248.75	0.5	92.91	105.92
maximum	5	15000	17100	7.5	10000	11400
Yam						
mean	2.69	13605	4081.57	2.9	6300	1890
minimum	0.5	1500	450	O.5	2500	750
maximum	4	3000	9000	7	11000	3300
Mean output			13201.14			4901.58
Std error			628.49			770.01
Std deviation			10899.48			5658.43
t-value				8.35**		

Source: Author's Computation, 2024

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Assessing the Policy Coherence and Coordination for Effective Climate-Smart Agriculture Strategies in Ghana

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Abstract

The agricultural sector in Ghana is highly susceptible to the adverse impacts of climate change, resulting in the implementation of climate-smart agriculture (CSA) practices and a transition towards a more resilient food system. To address this challenge, Ghana has developed various policies, strategies, and initiatives aimed at promoting sustainable agriculture and mitigating the effects of climate change. This research assesses the policy coherence and institutional coordination mechanisms for the effective implementation of CSA strategies in Ghana. Specifically, it examines the extent to which the various policies and strategies related to CSA and food system transition are consistent and complementary, evaluates the mechanisms for coordination and collaboration among government agencies, ministries, and stakeholders, analyzes stakeholder engagement processes, assesses resource allocation and monitoring frameworks, and identify potential barriers or challenges to policy implementation. By addressing these governance issues, the research provides valuable insights and recommendations to enhance the coordination, coherence, and effectiveness of CSA implementation efforts in Ghana. This, in turn, can contribute to a more sustainable and resilient food system transition, aligning with the country's commitment to addressing climate change, promoting sustainable agriculture, and achieving national development goals. The study is significant because strong governance and policy coherence are key to the successful implementation of CSA initiatives in Ghana.

Keywords: CSA, Ghana, Policy Coherence, Institutional Coordination

Introduction

Climate change represents one of the most pressing global challenges of the 21st century, with far-reaching implications for agricultural systems, food security, and rural livelihoods. This phenomenon, characterized by long-term changes in temperature, precipitation patterns, and the frequency of extreme weather events, poses a particularly significant threat to developing nations such as Ghana (FAO, 2015; Riedy, 2016; Tuebner, 2023). Ghana's high vulnerability to climate change stems from its substantial dependence on rain-fed agriculture, elevated poverty rates, and limited infrastructure development (Quarshie *et al.*, 2023; Li *et al.*, 2024; Anuga *et al.,* 2019). As such, the imperative to develop and implement effective strategies to mitigate and adapt to climate change impacts on agriculture has become increasingly urgent.

This paper aims to assess the policy coherence and coordination of Climate-Smart Agriculture (CSA) strategies in Ghana, examining the country's unique challenges, policy landscape, and commitment to addressing climate change impacts on agriculture. To provide a comprehensive foundation for this analysis, we will delve into the evolution of CSA policies and strategies in Ghana, highlighting key policy frameworks and their significance in the country's agricultural sector.

Ghana, like many countries in sub-Saharan Africa, has experienced significant climatic changes over the past century. Temperature trends have exhibited a steady rise, mirroring broader global warming patterns (Mensah *et al.*, 2021; Tuebner, 2023). Concurrently, shifts in rainfall patterns have been observed, with some regions witnessing changes in the timing, intensity, and distribution of precipitation, while others grapple with greater variability and unpredictability (Zubairu *et al.*, 2021). The frequency and intensity of extreme weather events, including floods, droughts, and storms, have also increased, disrupting livelihoods, damaging infrastructure, and posing risks to human safety and well-being (Tuebner, 2023).

The Agriculture, Forestry, and Other Land Use (AFOLU) sector has been identified as the largest contributor to these changes in Ghana, responsible for 54.4% of total emissions causing climate change captured in 2016, followed by the energy (35.6%) and waste (7.5%) sectors (Tuebner, 2023). This underscores the critical need for targeted interventions in the agricultural sector to address both mitigation and adaptation challenges.

The impacts of climate change in Ghana have manifested across several key development areas, with particularly significant consequences for food security, agriculture, water resources management, health, and economic growth (Tuebner, 2023). These impacts are projected to intensify in the coming decades, posing substantial challenges to Ghana's sustainable development aspirations.

The agriculture and livestock sectors are crucial to Ghana's food security and economy, employing approximately 45% of the workforce and contributing 21% to the Gross Domestic Product (GDP) as of 2021 (GIPC, 2022). However, the predominance of small, rain-fed farms renders the sector highly vulnerable to climate change impacts (Alua *et al.*, 2020). Rising temperatures are expected to significantly impact Ghanaian farmers by reducing crop yields (Amikuzino & Baffour-Ata *et al.*, 2021; Odame Appiah *et al.*, 2018; Klutse *et al.,* 2020). For instance, cassava yields are projected to decrease by 29.6% by 2080, while corn yields may decline by 7% by 2050 (USAID, 2011). Higher temperatures are likely to increase the prevalence of pests and diseases, further contributing to crop failure and lower yields (Alua *et al.*, 2020).

Moreover, suitable areas for cocoa production, a critical export crop for Ghana, are shrinking due to rising temperatures, floods, soil salinization, and ongoing coastal erosion (Tuebner, 2023). The livestock industry, which contributes over 8% to Ghana's GDP, is also impacted by climate change through heat stress and unpredictable rainfall, reducing fodder and water availability (Chemura *et al.*, 2020).

Water resources in Ghana are among the most sensitive sectors to climate change due to their direct relationship with climate variables (Ankomah-baffoe, 2021; Dovie *et al.,* 2017). Rising temperatures have reduced river runoff, while changes in precipitation have affected both runoff and groundwater recharge (Yeleliere *et al.,* 2018). Other impacts include lowered water tables, reduced stream flows, and diminished water availability in lakes and reservoirs, and salinization of estuaries and aquifers due to sea level rise (Tuebner, 2023). These changes have significant implications for human consumption, agriculture, industry, and hydropower generation.

Climate variability has direct implications for public health in Ghana (Adu-Prah *et al.*, 2019; Asante & Amuakwa-Mensah, 2014). It is estimated that more than half of the diseases in the country have a direct link to climate variability and exposure, with climate change potentially leading to higher infection rates of diseases such as malaria and meningitis (Codjoe *et al.,* 2020). Furthermore, climate change affects herders' migratory patterns and heightens competition for resources, which can intensify social tensions and lead to violence (Issifu *et al.*, 2022). Conflicts between farmers and herders over arable land, water, and crop damage from trespassing livestock can result in property destruction, armed robbery, ethnic marginalization, and violence.

In response to the multifaceted challenges posed by climate change in the agricultural sector, the concept of Climate-Smart Agriculture (CSA) has emerged as a comprehensive approach to enhance the resilience and productivity of agricultural systems while contributing to climate change mitigation and adaptation efforts (Quarshie *et al.,* 2023). CSA aims to transform agricultural production systems and food supply chains to promote sustainable development and ensure food security amidst a changing climate (Okolie *et al.,* 2022; Adesina & Loboguerrero, 2021; Vatsa *et al.,* 2023).

CSA Policies in Ghana

Ghana's agricultural and food systems heavily depend on climatic conditions, making them particularly vulnerable to climate change (Armah *et al.,* 2011; Derbile *et al.*, 2022; Yaro, 2013). Recognizing this vulnerability, Ghana formulated the National Climate Change Strategy in 2008, identifying ten cross-sectoral program areas for implementation. However, the lack of integration into sectoral policies and plans hindered their effectiveness (Essegbey *et al.*, 2015). To improve the implementation and address climate challenges, the National Climate Change Committee (NCCC) was established in 2010 under the Ministry of Environment, Science, and Technology.

The "Ghana Goes for Green Growth" (G4) played a significant role in shaping subsequent climate change policies (Essegbey *et al.*, 2015). This discussion paper provided a framework for climate change policy, emphasizing the need for adaptation and mitigation. The vision from G4 was incorporated into the 2012 National Climate Change Policy (NCCP), which outlined seven pillars: Governance and Coordination, Capacity Building, Research and Knowledge Management, Finance, International Cooperation, Communication, and Monitoring and Reporting (Environmental Protection Agency, 2020; Essegbey *et al.*, 2015; Palombi & Sessa, 2013). The NCCP is Ghana's comprehensive response to climate change, aligning with national sustainable development priorities.

Ghana's government recognizes the necessity of mainstreaming climate change into policies and sectoral activities for sustainable growth. The NCCP aims for a climate-resilient and climate-compatible economy, achieving sustainable development through low-carbon economic growth. The policy prioritizes five areas: Agriculture and Food Security, Disaster Preparedness and Response, Natural Resource Management, Equitable Social Development, and Energy, Industrial, and Infrastructural Development (Palombi & Sessa, 2013).

The significance of science and technology (S&T) in development led to the Ministry of Food and Agriculture (MoFA) developing the Climate-Smart Agriculture and Food Security Action Plan (CSAIP). This plan operationalizes the NCCP, reviewing relevant agricultural policies like the Food and Agriculture Sector Development Policy (FASDEP) and the Medium-Term Agriculture Sector Investment Plan (METASIP) to integrate CSA practices (World Bank, 2020). The CSAIP aims to identify CSA technologies that enhance productivity and resilience, ensuring environmentally sustainable agricultural practices (World Bank, 2020). It aligns with FAO's definition of CSA, focusing on increasing productivity, adaptation, and mitigation (Essegbey *et al.,* 2015).

The CSAIP prioritizes nine investments and actions to boost crop resilience and yields, benefiting 1.7 million people and helping them adapt to climate change (World Bank, 2020). It aligns with Ghana's goals to create jobs, improve value chains, reduce food imports, and increase exports, focusing on key crops and value chains like cocoa and fisheries (World Bank, 2020). The implementation supports national and international commitments, including the Agenda for Jobs, Comprehensive Africa Agriculture Development Program (CAADP), Sustainable Development Goals (SDGs), and the Nationally Determined Contributions (NDCs) to the Paris Agreement (Essegbey *et al.,* 2015).

Key CSA Strategies Shaping the Development of the CSAIP

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), Ghana has made significant strides in addressing climate change across various sectors (Awuni *et al.*, 2023; Lawson, 2016; Sova *et al.*, 2014). The country has prioritized climate change politically and integrated it into national development frameworks. A key framework is the Ghana Shared Growth and Development Agenda (GSGDA) (2010–2013), managed by the National Development Planning Commission (NDPC). This framework emphasizes climate change as a crucial element in development planning, particularly in agriculture and food security. The successor framework, GSGDA II, places further emphasis on environmental management. Supported by the National Environment Policy (NEP), it seeks to balance economic growth with environmental sustainability. The Food and Agriculture Sector Development Policy (FASDEP) II, which builds on the lessons from FASDEP I, promotes environmental sustainability and the use of science and technology to enhance productivity, with significant involvement from the private sector (Ghana National Development Planning Commission, 2014). To implement FASDEP II, the Medium-Term Agriculture Sector Investment Plan (METASIP) was created. METASIP focuses on land management, institutional collaboration, and agricultural innovation, specifying activities, lead agencies, and partners to ensure effective execution (MoFA, 2007b, 2007a). The Ghana Irrigation Policy aims to boost irrigated crop production by addressing issues related to productivity, land and water resource management, environmental degradation, and irrigation support (Ministry of Food and Agriculture, 2011). It encourages decentralization and private sector participation in the irrigation value chain (Ministry of Food and Agriculture, 2011). The Tree Crops Policy provides strategic actions for the sustainable development of tree crops like coconut, cashew, cocoa, rubber, kola, and shea nut (Mponela *et al.,* 2023). It focuses on value chain development and improved technologies to create jobs, ensure food security, protect the environment, and improve livelihoods (Yeboah-Assiamah *et al.*, 2023. It also addresses environmental impacts such as pollution and deforestation while promoting benefits like carbon sequestration and soil conservation. Additional policies include the Ghana Strategic Investment Framework (GSIF) for Sustainable Land Management (SLM), addressing land degradation and promoting sustainable land management; the National Action Programme to Combat Drought and Desertification (NAP-CDD), tackling drought and desertification in vulnerable zones; and the National Climate Change Policy – Action Programme for Implementation 2015 – 2020, which provides a national framework for implementing the Agriculture and Food Security component of the National Climate Change Policy (MESTI, 2015; FAO, 2002). These policies collectively aim to enhance Ghana's agricultural resilience, ensure sustainable development, and integrate climate change considerations into national and sectoral activities.

Theoretical Framework

Overview of Policy Coherence Theory

Policy coherence has emerged as a crucial concept in development studies, policy sciences, and public administration, emphasizing the need for consistency and alignment among policies across different sectors and levels of government (Guerrero & Castañeda, 2021). Policy coherence, in simple terms, is the idea that different policies should work together towards the same goals. This is especially important in fields like environmental governance, where policies from different sectors can affect each other (Coscieme *et al.,* 2021). For example, agricultural policies that encourage deforestation could undermine climate change mitigation efforts. Policy coherence is increasingly recognized as crucial for effective environmental governance, especially given the interconnected nature of environmental issues and their linkages with social and economic goals (Yunita *et al.,* 2022; Fopa Tchinda & Talbot, 2024; Shawoo *et al.,* 2023; Righettini & Lizzi, 2022). The 2030 Agenda for Sustainable Development, with its 17 Sustainable Development Goals (SDGs), explicitly emphasizes policy coherence as both a means and an end to achieve sustainable development (Yunita *et al.,* 2022; Shawoo *et al.,* 2023). However, there are critiques regarding the current understanding and application of policy coherence for sustainable development. Critics argue that the dominant framing of policy coherence as a technical challenge overlooks the inherently political nature of sustainable development and the trade-offs involved (Yunita *et al.,* 2022; Shawoo *et al.,* 2023). Furthermore, the focus on institutional arrangements and coordination mechanisms often fails to address the underlying power imbalances and vested interests that shape policy decisions (Yunita *et al.,* 2022; Shawoo *et al.,* 2023). Moreover, the concept of sustainable development itself, around which policies are meant to cohere, is often criticized for its ambiguity and susceptibility to co-optation by actors with different, even opposing agendas (Yunita *et al.,* 2022).

To address these critiques, it is crucial to consider the political drivers of policy coherence. The comparative politics literature offers a valuable lens through which to understand how factors like ideas, institutions, and interests influence policy coherence (Shawoo *et al.,* 2023). These encompass the underlying values, assumptions, problem definitions, and policy paradigms that shape how actors perceive and address sustainable development challenges (Shawoo *et al.,* 2023). Institutions refer to the formal and informal rules, norms, and procedures that structure decision-making processes and influence the distribution of power among actors (Shawoo *et al.,* 2023). Interests relate to the motivations, preferences, and strategies of various stakeholders involved in the policy process, including government agencies, businesses, civil society organizations, and citizens (Shawoo *et al.,* 2023). Analyzing these political drivers can provide valuable insights into why certain policy choices are made, who benefits from (or is disadvantaged by) specific policy configurations, and how power dynamics influence the pursuit of policy coherence (Shawoo *et al.,* 2023).

Policy coherence is essential for the effective implementation of climate-smart agriculture (CSA) strategies. Inconsistencies or contradictions between policies from different sectors can undermine CSA initiatives and create perverse incentives. Challenges to achieving policy coherence in this context include silo mentalities among government departments, lack of political will, data limitations for assessing policy interactions, complexity of policy processes, and conflicting interests among stakeholders (Righettini & Lizzi 2022; Brand *et al.,* 2021).

Governance and Institutional Coordination Theory

Effective policy coordination is imperative for addressing complex, cross-cutting issues that require a "whole-of-government" approach (Molenveld et al., 2020). Coordination mechanisms can take various forms, including rule-based coordination (legislation, regulations), organizational coordination (dedicated coordinating bodies), strategic policy coordination (integrated strategies), and policy instrument coordination (aligning incentives across sectors) (Ferry, 2021). The success of these mechanisms hinges on navigating institutional contexts (power dynamics, resource distribution), cognitive framing (shared understanding), and political economy factors (political will, vested interests) (Ferry, 2021). A pluricentric perspective acknowledges the multiple actors influencing policy processes, necessitating a shift from vertical command-and-control approaches to horizontal, collaborative models (Reff Pedersen et al., 2011; Wang & Ran, 2023).

Diverse theoretical lenses offer valuable insights into coordination dynamics. The hierarchical-instrumental perspective emphasizes central control and top-down coordination, while the negotiation-instrumental approach advocates a balance between central guidance and local autonomy through collaborative goal-setting and negotiated mandates (Corcaci, 2023; Molenveld *et al.,* 2020). The cultural-institutional perspective highlights the role of shared values, norms, and trust in fostering coordination, while the myth-institutional lens cautions against superficial coordination efforts driven by symbolic motivations rather than substantive collaboration (Molenveld *et al.,* 2020). Effective coordination often requires an understanding of these perspectives and the strategic employment of hybrid approaches that combine and sequence different mechanisms adaptively based on evolving needs and contexts.

Institutional frameworks play a critical role in shaping policy implementation and coordination processes (Sager & Gofen, 2022; Ssennyonjo *et al.,* 2022; von Lüpke *et al.,* 2023). Dynamic linkages, facilitated through communication and interaction across levels (individual, organizational, institutional), are essential for maintaining responsiveness and adaptability to changing environments (Reff Pedersen *et al.,* 2011; Wang & Ran, 2023). Situated coordination emphasizes context-specific approaches tailored to unique factors, such as trust dynamics, power relations, and the nature of the policy problem at hand (Reff Pedersen *et al.,* 2011). Collaborative storytelling and meaning-making processes help actors negotiate understanding, build consensus, and navigate tensions inherent in collaborative governance arrangements (Reff Pedersen *et al.,* 2011). Ultimately, a pluricentric perspective on policy coordination acknowledges the emergent and potentially unpredictable nature of policy outcomes. Continuous interaction, negotiation, and learning among actors are crucial for mitigating conflicts, fostering dynamic equilibrium, and ensuring effective implementation within the policy arena.

Application and Relevance to Climate-Smart Agriculture

The theoretical framework highlights the interconnected nature of environmental challenges, which aligns with the goals of CSA. CSA strategies simultaneously aim to address climate change mitigation and adaptation, sustainable food production, and rural development objectives. This interconnectedness requires policy coherence across different sectors. These theories acknowledge the inherently political nature of sustainable development and the role of ideas, institutions, and interests in shaping policy decisions. This resonates with the complexities surrounding CSA implementation, where competing paradigms, power dynamics, and stakeholder interests can significantly influence the adoption and prioritization of CSA practices. Furthermore, emphasis on governance and institutional coordination aligns with the cross-cutting nature of CSA strategies. Specifically, CSA initiatives require coordination among various sectors, including agriculture, environment, energy, and rural development, requiring effective coordination mechanisms and collaborative approaches.

The theoretical framework provided can serve as a valuable conceptual foundation for studying policy coherence and coordination dynamics in the context of CSA strategies. It offers a comprehensive lens through which to analyze the institutional, political, and contextual factors influencing CSA implementation. Additionally, the governance and institutional coordination theories provide analytical tools to examine the effectiveness of various coordination mechanisms and the potential for hybrid approaches tailored to the specific needs of CSA initiatives.

Methodology

This study employs a qualitative approach to assess the policy coherence and coordination of Climate-Smart Agriculture (CSA) strategies in Ghana. The methodology comprises a comprehensive content analysis of relevant policy documents and support for CSA initiatives. The content analysis commences with the identification and selection of key policy documents pertaining to agriculture, climate change, and related sectors in Ghana. The selection criteria prioritize documents that explicitly reference "Climate-Smart Agriculture" or analogous terms such as "climate-resilient agriculture" and "sustainable agriculture." The corpus of documents includes, the Coordinated Programme of Economic and Social Development Policies (2003-2024), Ghana Shared Growth and

Development Agenda (GSGDA I & II) 2010-2017, Growth and Poverty Reduction Strategy (GPRS I & II) 2003-2009, the National Climate Change Policy (NCCP), the National Agriculture Policy, Ghana's Nationally Determined Contributions (NDCs), and the Medium Term Expenditure Framework for the Ministry of Food and Agriculture.

A coding framework is developed to systematically analyze these documents. This framework encompasses codes and categories related to CSA strategies, including specific CSA practices, policy objectives and targets, institutional arrangements for implementation, and support mechanisms. The coding process is executed with attention to inter-coder reliability to ensure objectivity and consistency in the analysis.

The coded data is subsequently subjected to rigorous analysis to identify patterns, trends, and relationships within and across different policy documents. This analysis focuses on two key dimensions: policy coherence and policy coordination. The assessment of policy coherence examines the consistency and alignment of objectives, targets, and strategies related to CSA across various policy documents, identifying any contradictions or inconsistencies that may impede effective implementation. The evaluation of policy coordination scrutinizes the institutional arrangements and coordination mechanisms delineated in the policies, determining the clarity of roles and responsibilities, communication channels, and collaborative platforms for diverse stakeholders involved in CSA implementation.

Findings

Policy Coherence and CSA in Ghana

The analysis of Ghana's policy documents from 2003 to 2024 reveals a gradual evolution in policy coherence concerning Climate Smart Agriculture (CSA). This progression demonstrates an increasing awareness of the interconnectedness between agricultural development, environmental sustainability, and climate resilience. The Ghana Poverty Reduction Strategy (GPRS) 2003-2005 laid the foundation for integrating agricultural development with environmental considerations. While not directly addressing CSA, it emphasized sustainable natural resource management and cross-sectoral coordination, providing an initial framework for future CSA-aligned policies.

The Ghana Poverty Reduction Strategy II (GPRS II) 2006-2009 marked a significant advancement, introducing a more comprehensive approach to agricultural modernization and environmental sustainability. This iteration demonstrated increased policy coherence by linking productivity goals with environmental protection, aligning more closely with CSA principles. The Ghana Shared Growth and Development Agenda (GSGDA) 2010-2013 and 2014-2017 further refined these approaches, introducing specific policy instruments such as Agricultural Mechanization and Service Centres (AMSEC) and the Agricultural Development Fund. These policies exhibited greater coherence in addressing agricultural productivity and environmental sustainability, though still lacking explicit CSA terminology. The Coordinated Programme of Economic and Social Development Policies (2017-2024) recognized of climate change impacts on agriculture. Initiatives like "Planting for Food and Jobs" and "One Village, One Dam" reflect a growing alignment with CSA principles, integrating productivity enhancement with climate resilience strategies.

Throughout the policy evolution, several cross-cutting themes emerge that demonstrate increasing coherence with CSA principles. Specifically, all policies consistently emphasize increasing agricultural productivity, aligning with CSA's goal of enhancing food security (Table 1). The recognition of environmental concerns has been consistent across all policies, evolving from broad statements in the GPRS 2003-2005 to more targeted approaches in later policies. While early policies lacked explicit climate change considerations, later documents, demonstrate a clear integration of climate resilience strategies in agricultural development.

Consistency and Complementarity of Policies

The examination of policy coherence concerning Climate Smart Agriculture (CSA) in Ghana, as evidenced by the policy documents spanning from 2003 to 2024, reveals a gradual evolution in the country's approach to sustainable agricultural development and climate change mitigation. This analysis focuses on the consistency and complementarity of these policies, as well as their implementation through illustrative case studies. The policy documents demonstrate a progressive alignment towards more integrated and holistic approaches to agricultural development, with an increasing emphasis on environmental sustainability and climate resilience. The Ghana Poverty Reduction Strategy (GPRS) 2003-2005 recognized the need for inter-ministerial coordination and the integration of biodiversity concerns into development planning. This approach was further refined in subsequent policies, culminating in the Coordinated Programme of Economic and Social Development Policies (CPESDP), which explicitly advocates for a restructuring of key institutions to support a more coherent and demand-driven agricultural sector. The NCCP acknowledges the particular vulnerability of Ghana's agriculture sector due to its reliance on rainfall and the limited resources of small-scale farmers. This recognition highlights the NCCP's consistency with the core principles of CSA (Table 1). The NCCP promotes institutional capacity-building, emphasizing training at district levels for local initiative implementation. Acknowledging the role of science, technology, and innovation, the NCCP recommends establishing a Centre for Excellence for Climate to bridge research and knowledge gaps and endorse a multi-disciplinary research approach to understand the complexities of climate change (MESTI, 2013). For financial sustainability, the NCCP proposes a national financing mechanism or facility to manage climate finance effectively. Additionally, the NCCP aligns with international agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (MESTI, 2013).

All the policies consistently emphasize the need for enhanced collaboration between relevant ministries, departments, and agencies. This alignment creates a conducive environment for implementing CSA practices, which inherently require cross-sectoral approaches. There is also a progressive increase in emphasis on public-private partnerships across the policies, culminating in the CPESDP's proposal for District Chambers of Agriculture, Commerce and Technology (DCACT). This evolution aligns well with CSA principles, which often require private sector investment and innovation.

Case Studies of Policy Implementation

The evolution of Ghana's cocoa sector policies provides an example of policy coherence in action. The GPRS 2003-2005 highlighted the Ghana Cocoa Board (COCOBOD) as a model for other cash crops. Subsequent policies built on this foundation, with the CPESDP 2017-2024 proposing similar marketing boards for oil palm, cotton, and horticulture. This consistent policy direction has facilitated the implementation of CSA practices in the cocoa sector, such as agroforestry systems and drought-resistant varieties, demonstrating how policy coherence can drive sustainable agricultural practices.

The trajectory of agricultural financing policies across the documents illustrates both progress and challenges in policy coherence. The GPRS 2003-2005 identified the need for coordination between economic and trade ministries to remove production and marketing constraints. The CPESDP 2017-2024 builds on this by proposing "tailor-made agricultural financing." However, the implementation of these financing mechanisms has been inconsistent, with gaps in addressing the specific needs of smallholder farmers adopting CSA practices.

Furthermore, the transformation of inter-ministerial coordination also provides insights into policy coherence. The GPRS identified the need for coordination between economic and trade ministries to address marketing and production constraints. This approach was expanded in the GSGDA 2010-2013, which proposed a platform for joint planning and review. The CPESDP 2017-2024 takes this further by proposing structural changes, such as introducing a marketing department in the Ministry of Food and Agriculture to work with the Ministry of Trade and Industry. Another case study is the integration of biodiversity and environmental concerns into agricultural policies. The policies acknowledged the need to mainstream environmental measures into production practices.

However, persistent challenges remain. While coordination mechanisms have improved, the policies still tend to address agricultural productivity, environmental conservation, and climate change as separate issues rather than integrated components of a CSA approach. The lack of explicit references to CSA in these policies suggests that Ghana's development strategies may not fully capitalize on the potential synergies between agricultural development, climate adaptation, and mitigation.

Institutional Coordination Mechanisms

The successful implementation of CSA policies requires institutional coordination mechanisms to ensure coherence and effectiveness across various governmental and non-governmental entities. For instance, under MoFA's 2020 Medium Term Expenditure Framework, the institutional framework for CSA in Ghana is characterized by a multitude of agencies and ministries, each contributing unique expertise and resources. The Ministry of Food and Agriculture (MOFA) serves as the primary government body responsible for agricultural policy formulation and implementation. Within MOFA, several directorates play pivotal roles in CSA-related activities such as Directorate of Crop Services (DCS), Directorate of Agricultural Extension Services (DAES), Statistics Research and Information Directorate (SRID), Women in Agricultural Directorate (WIAD), Policy Planning Monitoring and Evaluation Directorate (PPMED). Other key institutions include the Ghana Irrigation Development Authority (GIDA), Plant Protection and Regulatory Services Directorate (PPRSD), Veterinary Services Directorate (VSD), Animal Production Directorate (APD), Grains and Legumes Development Board (GLDB), and the National Food Buffer Stock Company (NAFCO) (MoFA, 2020).

The Directorate of Crop Services plays a central role in CSA implementation, particularly through its Climate Change Resilience and Mitigation sub-programme. This initiative aims to enhance institutional capacity for climate-resilient agricultural development and increase the resilience of agricultural production systems against global climate change (MoFA, 2020). The Directorate of Agricultural Extension Services is instrumental in disseminating CSA practices to farmers, leveraging its network of Agricultural Extension Agents (AEAs) to promote technology adoption and knowledge transfer. GIDA focuses on irrigation and water management, which are critical components of CSA. The authority works on expanding access to irrigated agriculture and ensuring the sustainability and efficiency of irrigation schemes. PPRSD and VSD contribute to CSA through their roles in pest and disease management, which are increasingly important in the face of climate-induced changes in pest and disease patterns. The Statistics Research and Information Directorate plays a crucial role in providing timely and reliable data for policy formulation and decision-making related to CSA. This includes maintaining a computer database for the agricultural sector and promoting e-agriculture to support operations.

The institutional framework for CSA in Ghana is supported by formal coordination structures that facilitate inter-agency collaboration. These include inter-ministerial committees, technical working groups and joint implementation committees. For instance, the programme structure for MoFA suggests some inherent coordination mechanisms. Furthermore, the organization of activities under specific programmes and sub-programmes (e.g., Sustainable Management of Land and Environment) implies a level of inter-directorate coordination. Flagship programmes like Planting for Food and Jobs (PFJ) and Rearing for Food and Jobs (RFJ) requires collaboration across multiple directorates. Moreover, the involvement of multiple international donors (e.g., CIDA, World Bank, USAID) in various sub-programmes suggests potential for donor-driven coordination platforms (MoFA, 2020).

Complementing the formal structures is informal coordination through the overlapping responsibilities of different directorates. The effectiveness of these coordination mechanisms varies. While formal structures provide a solid foundation for inter-agency collaboration, they sometimes face challenges such as bureaucratic inertia and resource constraints. Informal mechanisms often prove more agile but may lack the authority to effect systemic changes. For instance, under MoFA's 2020 Medium Term Expenditure Framework, the mention of "weak collaboration among key stakeholders" as a challenge in the Early Warning Systems and Emergency Preparedness sub-programme suggests room for improvement in coordination efforts (MoFA, 2020). Furthermore, the sub-programme on Climate Change Resilience and Mitigation, implemented by the Directorate of Crop Services, demonstrates a coordinated approach to CSA. However, the programme description notes challenges such as high staff attrition rates, which may impede long-term coordination efforts (MoFA, 2020).

Ghana employs various methods to engage stakeholders in CSA policy processes. This includes Public-Private-Producer-Partnership (PPPP) arrangements in the context of irrigation development, suggesting a multi-stakeholder approach (MoFA, 2020). Other stakeholder engagements include bringing together government agencies, farmers' organizations, NGOs, and private sector entities to provide input on CSA policies and strategies (MoFA, 2020). For instance, the formation and capacity building of Water Users Associations (WUAs) indicates engagement with local water users in irrigation management. Another primary method of engaging farmers is through extension services and e-agriculture initiatives (MoFA, 2020).

Ghana employs various methods to engage stakeholders in CSA policy processes (Sam et al., 2020; Damba et al., 2021; Diko et al., 2021). This includes Public-Private-Producer-Partnership (PPPP) arrangements, Water Users Associations (WUAs), extension services, and e-agriculture initiatives (MoFA, 2020). These engagement methods are intricately linked to the implementation of programmes such as the Savannah Zone Agriculture Productivity Improvement Project (SAPIP) and the Savannah Improvement Programme (SIP), both of which are funded by the African Development Bank (AfDB) and focus on the Northern Savannah Ecological Zone (MoFA, 2021). The PPPP approach is exemplified in the implementation of SAPIP, where the project aims to establish three Mechanized Service Centres through Public-Private Partnership (PPP) arrangements (MoFA, 2021). This initiative will equip these centers with advanced agricultural machinery, including ten 18-row capacity Seed rills, five 1000Kg grain tank Combine Harvesters, and other specialized equipment (MoFA, 2021). This partnership not only enhances stakeholder involvement but also promotes institutional coordination between the public sector and private entities in the agricultural mechanization domain (MoFA, 2021).

Extension services and e-agriculture initiatives play a crucial role in disseminating CSA practices to farmers. This is evident in the programme's plan to enhance the capacity of extension staff on climate change, enabling them to provide climate-responsive services to 5,000 smallholder farmers (MoFA, 2021). Furthermore, the use of the Farmer Field Business School (FFBS) approach to establish demonstrations on conservation agriculture in 39 districts illustrates how stakeholder engagement methods are integrated into programme implementation (MoFA, 2021).

The programmes' implementation showcases significant institutional coordination and collaboration. For example, the Ministry of Food and Agriculture's collaboration with the Food and Agriculture Organization of the United Nations (FAO) to sensitize 1,306 farmers (818 males and 488 females) from 11 districts on establishing 33 Conservation Agriculture demonstrations highlights international partnership in promoting CSA practices (MoFA, 2021).

Stakeholder involvement in CSA policy processes in Ghana is characterized by a growing recognition of the need for inclusive participation. The Medium Term Expenditure Frameworks highlights the importance of engaging various stakeholders, including farmers, private sector entities, and international donors (MoFA, 2020; 2021). However, challenges persist in ensuring comprehensive stakeholder engagement. The high cost and limited access to agricultural inputs, noted as issues in the Production and Productivity Improvement sub-programme, suggest that smallholder farmers' voices may not be adequately represented in policy formulation. The emphasis on promoting e-agriculture and improving public access to information, as mentioned in the Research, Statistics, Information and Communication sub-programme, indicates efforts to enhance stakeholder engagement through improved information dissemination.

The implementation of various agricultural programmes under the MTEFs is crucial for climate smart agriculture strategies in Ghana. The substantial increase in irrigated area indicates a strong focus on water management which constitutes a key component of CSA, as it helps mitigate the impacts of erratic rainfall patterns associated with climate change. The Early Warning Systems and Emergency Preparedness sub-programme also demonstrates Ghana's commitment to building resilience against pests, particularly the Fall Army Worm. The area recovered indicator shows a significant increase from 66,000 ha in 2021 to a projected 200,500 ha in 2024. This upward trend suggests an enhanced capacity to respond to pest-related emergencies, which is crucial for maintaining agricultural productivity in the face of climate-induced pest pressures. The MTEFs demonstrates vertical integration by linking national-level programmes to farm-level interventions. This is evident in the progression from institutional capacity building (e.g., training agriculture staff) to on-the-ground implementation (e.g., area recovered, farmers adopting CSA practices) (Table 2). Furthermore, the presence of a Ministerial Climate Change Task Force indicates an effort towards horizontal coordination across different government departments. However, the relatively low frequency of meetings (1-4 per year) might be insufficient for effective coordination given the complex, cross-cutting nature of CSA. The frameworks also demonstrate temporal coherence, allowing for short to medium-term planning. This temporal coherence is crucial for the gradual implementation and scaling up of CSA strategies.

Conclusion

This comprehensive analysis of policy coherence and coordination for Climate-Smart Agriculture (CSA) strategies in Ghana provides some insights into the country's evolving approach to sustainable agricultural development and climate change mitigation. The study, which evaluated policy documents spanning from 2003 to 2024 and assessed institutional coordination mechanisms, provides a varied picture of progress and ongoing problems in Ghana's efforts to implement successful CSA measures.

The longitudinal analysis of policy documents demonstrates a gradual but discernible evolution towards greater coherence in addressing the interconnected challenges of agricultural productivity, environmental sustainability, and climate resilience. The progression from the Ghana Poverty Reduction Strategy (GPRS) of 2003-2005 to the Coordinated Programme of Economic and Social Development Policies (CPESDP) of 2017-2024 evinces an increasing recognition of the nexus between agricultural development and climate change. However, the analysis also reveals that while policy coherence has improved over time, there remains a lack of explicit references to CSA in many key documents. This suggests that Ghana's development strategies may not fully capitalize on the potential synergies between agricultural development, climate adaptation, and mitigation. The persistence of this gap indicates a need for more deliberate integration of CSA principles into future policy formulations.

The examination of institutional coordination mechanisms reveals a landscape of governmental and non-governmental entities involved in CSA implementation. The Ministry of Food and Agriculture (MOFA) emerges as the primary coordinating body, with various directorates and agencies playing crucial roles in different aspects of CSA. The presence of formal coordination structures, such as inter-ministerial committees and technical working groups, provides a foundation for inter-agency collaboration. However, the effectiveness of these mechanisms varies, with some sub-programmes reporting weak collaboration among key stakeholders.

The findings on stakeholder engagement methods indicate a growing recognition of the importance of inclusive participation in CSA policy processes. The implementation of Public-Private-Producer-Partnership (PPPP) arrangements demonstrates efforts to involve diverse stakeholders. However, challenges persist in ensuring comprehensive stakeholder engagement, particularly in representing the voices of smallholder farmers in policy formulation.

These findings have significant implications for the implementation of CSA strategies in Ghana. While the country has made progress in aligning its agricultural policies with CSA principles, there is a clear need for more explicit and coordinated integration of these principles across all relevant policy domains. The gradual improvement in policy coherence provides a foundation upon which more targeted CSA interventions can be built, but realizing the full potential of these strategies will require addressing the identified gaps in coordination and stakeholder engagement.

Based on these findings, several recommendations can be made to enhance policy coherence and coordination for CSA in Ghana. Specifically, an explicit integration of CSA terminology and principles into all relevant policy documents to ensure a unified and coherent approach across sectors. Secondly, efforts must be made to strengthen institutional coordination mechanisms, particularly in areas where weak collaboration has been identified. Furthermore, stakeholder engagement processes should be enhanced to ensure more comprehensive representation, especially of smallholder farmers and marginalized groups.

It is important to acknowledge the limitations of this study, which primarily focused on policy documents and institutional frameworks. Future research could benefit from incorporating field-level assessments of CSA implementation and its impacts on agricultural productivity, environmental sustainability, and climate resilience. Additionally, comparative studies with other countries in the region could provide valuable insights into best practices for CSA policy coherence and coordination.

In conclusion, this study reveals that Ghana has made significant progress in aligning its agricultural policies with CSA principles, but there is still considerable room for improvement in terms of policy coherence and institutional coordination. The findings highlight the importance of continued efforts to integrate CSA strategies into Ghana's broader development agenda.

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Appendix

Table 1: Analysis of CSA-related Policies and Strategies

Policy	Detailed Examination of Key Policies	Assessment of Policy Goals, Objectives, and Instruments		
		Agricultural productivity and food security	**Environmental sustainability and climate change adaptation**	**Cross-sectoral coordination and policy coherence**
Ghana Poverty Reduction Strategy (GPRS) 2003-2005	Agricultural sector policies focus on modernizing agriculture and promoting agro-processing based on rural development. Key elements include: 1. Promotion of farm mechanization and irrigation facilities 2. Improvement of inputs for livestock and crop production 3. Encouragement of cash crop production, such as cashew for export 4. Development and multiplication of new improved varieties of seeds and planting materials 5. Emphasis on soil fertility and plant nutrition management 6. Promotion of integrated pest management practices Environmental and natural resource management policies encompass: 1. Mainstreaming environmental protection measures into current production practices 2. Implementing a national land use plan and soil fertility management action plan 3. Protecting, rehabilitating, and sustainably managing land use, forest, and wildlife resources 4. Incorporating aquaculture and livestock watering in irrigation infrastructure development 5. Implementing afforestation programmes that incorporate aquaculture projects and minimize pollution of coastal areas and water bodies	- Increasing agricultural growth from 4.1% per annum in 2002 to 4.8% per annum by 2005 - Developing improved varieties and breeds for crops and livestock - Enhancing extension services to improve production methods	- Encouraging conservation and sustained use of biodiversity - Rehabilitating threatened ecosystems and habitats using the Ecosystem Approach - Providing irrigation facilities, particularly in drought-prone areas - Supporting reforestation of degraded forests and abandoned mining areas	- Improving inter-ministerial coordination for increased production - Ensuring convergence of policies to remove marketing and production constraints - Integrating environmental conventions and protocols into national programmes

Ghana Poverty Reduction Strategy II (GPRS II) 2006-2009	1. Land reform and property rights: The strategy emphasizes reexamining access and control over land to promote equity and protect small holders' interests. This aligns with CSA's principle of enhancing resource use efficiency and resilience. 2. Irrigation infrastructure: GPRS II prioritizes the rehabilitation, expansion, and promotion of existing irrigation facilities, along with the development of small-scale community-based valley-bottom irrigation schemes. This focus on water management is crucial for climate resilience in agriculture. 3. Crop and livestock development: The strategy promotes the development of key selected crops with potential for food security, agro-industry, and export. It also emphasizes improved livestock breeds and husbandry practices. These policies align with CSA's goal of sustainable intensification. 4. Mechanization and extension services: The strategy promotes increased mechanization and the development of small-scale technologies targeting smallholder farmers. It also aims to expand the coverage and effectiveness of extension services. These interventions support CSA's objective of enhancing adaptive capacity and knowledge transfer. 5. Environmental restoration and conservation: GPRS II outlines strategies to stem land degradation, regulate climate variability impacts, promote integrated ecosystem management, and encourage reforestation. These policies directly address CSA's focus on mitigation and adaptation to climate change.	- Achieving 6% annual growth in agriculture - Developing and multiplying new and improved seeds - Promoting soil fertility management systems - Improving animal husbandry practices	- Initiating measures to stem land degradation and regulate climate variability impacts - Promoting integrated ecosystem management - Encouraging reforestation of degraded forest and off-reserve areas - Developing a sustainable strategy for forest and wildlife to support eco-tourism	- Promoting a multi-agency approach to enhance resource management and the environment - Linking agricultural modernization with human resource development and the application of research, science, and technology - Integrating pest and disease management systems into crop development strategies

National Climate Change Policy (NCCP) 2012	To ensure a climate-resilient and climate-compatible economy while achieving sustainable development through equitable low-carbon economic growth for Ghana.	-improve and harmonize research activities in climate-smart agriculture, -strengthen the capacities of extension officers - promote capacity-building for farmers and fisherfolk. -encourage the documentation and promotion of indigenous knowledge and best practices for building climate-resilient cropping and livestock systems.	-aims to minimize carbon sink loss by curbing activities like deforestation and forest degradation. -aims to enhance carbon stocks via programmes that restore degraded forests and ecosystems. -enhance the management and conservation of diverse ecosystems (terrestrial, aquatic, and marine) to bolster their resilience against climate change.	-the NCCP identifies seven foundational systemic pillars: governance and coordination, capacity-building, science, technology and innovation, finance, international cooperation, information, communication and education, and monitoring and reporting.

Ghana Shared Growth and Development Agenda (GSGDA) 2010-2013	1. Land and water management: The GSGDA prioritizes the development of irrigation infrastructure, including small-scale community-based valley-bottom schemes and groundwater exploitation. It also emphasizes sustainable land management practices and the creation of land banks to improve access to land for agricultural purposes. 2. Crop and livestock development: The strategy promotes the diversification of agricultural production, focusing on selected crops for food security, export revenue, and industrial raw materials. It also emphasizes improved livestock breeds and husbandry practices. 3. Mechanization and extension services: The GSGDA emphasizes accelerating agricultural mechanization through private sector involvement in producing and assembling appropriate machinery. It also focuses on improving access to extension services, particularly for women farmers and through the use of pluralistic extension methods. 4. Sustainable land use and biodiversity conservation: The strategy outlines policies for mainstreaming biodiversity issues into development planning, promoting sustainable forest management, and encouraging appropriate land use practices to combat degradation.	- Achieving 6% annual growth in the agricultural sector - Promoting the development of selected staple and cash crops - Improving post-harvest management and market access - Enhancing livestock and aquaculture production	- Mainstreaming sustainable land and environmental management practices in agriculture - Promoting the use of early warning meteorological information systems - Encouraging afforestation and reforestation of degraded lands - Implementing appropriate soil conservation techniques	- Strengthening intra-sectoral and inter-ministerial coordination - Creating a framework for coordinating activities among diverse stakeholders - Integrating biodiversity issues into development planning across sectors - Promoting public-private partnerships in agricultural development

Ghana Shared Growth and Development Agenda (GSGDA) 2014-2017	1. Agricultural Productivity and Food Security: The GSGDA outlines strategies to enhance agricultural productivity, including promoting the application of fertilizers, accelerating mechanization, and strengthening Research-Extension-Farmer Linkages (RELCs). These align with CSA's goal of sustainably increasing productivity. The policy also emphasizes the development of climate-resilient crop varieties, which directly supports CSA objectives. 2. Climate Change Adaptation and Mitigation: The document acknowledges the risks associated with rain-fed agriculture and proposes irrigation development as a mitigation strategy. This aligns with CSA's focus on building resilience to climate variability. Furthermore, the policy promotes the use of early warning meteorological information in agriculture, which is crucial for climate change adaptation. 3. Sustainable Land and Environmental Management: The GSGDA emphasizes mainstreaming sustainable land and environmental management practices in agriculture sector planning and implementation. This directly corresponds to CSA principles of sustainable resource management and climate change mitigation.	- Fertilizer subsidies and mechanization services - Establishment of Agriculture Mechanization and Service Centres (AMSECs) - Promotion of organic farming - Development of irrigation infrastructure - Implementation of the Ghana Irrigation Development Policy	These instruments, while not explicitly framed as CSA measures, have the potential to contribute to CSA objectives if implemented with consideration for climate resilience and sustainability.	Emphasis on cross-sectoral coordination, particularly in areas such as land use planning and climate change response, indicates a degree of policy coherence that could facilitate the implementation of CSA approaches.

Ghana Agricultural Investment Plan (GhAIP) 2018-2021	The GhAIP leverages an instrument-based approach to achieve its ambitious goals. These instruments are embedded within four comprehensive programmes: sector management and administration, crops and livestock development, agribusiness development, and sustainable management of land and the environment.	-Planting for Food and Jobs (PFJ) campaign. -Provision of subsidised inputs like seeds and fertilisers. -Recruitment and deployment of Agricultural Extension Agents. -Facilitation of market linkages and promoting value addition. -Enhancing the MoFA e-agriculture platform	-Conservation of natural resources management schemes. -Protection and conservation of biologically diverse ecosystems. -Promotion of sustainable forest management practices. -Research and knowledge dissemination on climate change mitigation and adaptation schemes. -Promoting green/growth agriculture concepts and principles.	-Establishment of a robust sector management and administration framework. -Emphasis on policy planning, budgeting, monitoring, evaluation, and coordination. -Collaboration with other Ministries, Departments, and Agencies (MDAs). -Involvement of the Private Enterprise Federation (FAGE) in key initiatives. -Harmonisation and alignment of Government and Donor interventions.

The Coordinated Programme of Economic and Social Development Policies (2017-2024)	Ghana's agricultural policies, particularly the "Planting for Food and Jobs" initiative, demonstrate a shift towards CSA-aligned practices. This program emphasizes improved seeds, fertilizer supply, dedicated extension services, and e-agriculture, all of which are consistent with CSA's aim to increase productivity sustainably. The "One Village, One Dam" initiative further supports CSA by promoting year-round farming and water management, crucial for climate resilience. The document outlines Ghana's commitment to climate change mitigation and adaptation through its National Climate Change Policy (NCCP). This policy provides strategic direction for achieving climate-resilient and low-carbon economic growth, aligning with CSA principles. The recognition of Ghana's vulnerability to climate change impacts, such as flooding, drought, and declining soil fertility, underscores the need for CSA approaches in the agricultural sector.	Policy goals and objectives supporting CSA are evident in several areas. The agricultural sector's projected growth rate of 6% annually, supported by interventions in crops, livestock, and fisheries sub-sectors, indicates a focus on productivity enhancement – a key CSA pillar. The emphasis on agro-industrial enterprises and the "One District, One Factory" initiative suggests a move towards value addition and economic resilience, which are important aspects of CSA.	Policy instruments promoting CSA include subsidies on retail prices of seeds, fertilizers, and agrochemicals, as well as the provision of critical infrastructure such as feeder roads, electricity, and water. The document also mentions customized agricultural financing and needs-based technical assistance, which can support the adoption of CSA practices.	The analysis reveals some gaps in policy coherence. While there is a clear focus on agricultural productivity and some aspects of climate resilience, explicit links between agricultural policies and climate change mitigation are less evident. The document acknowledges that the Agriculture, Forestry, and Other Land Uses (AFOLU) sector is the largest contributor to greenhouse gas emissions (45%), but specific policies targeting emissions reduction in agriculture are not clearly articulated. The integration of CSA principles across different sectors shows mixed results. There is evidence of cross-sectoral thinking, such as the link between agricultural development and industrial growth through the "One District, One Factory" initiative. However, stronger integration between agricultural policies and natural resource management, particularly in areas like forestry and water resources, could enhance policy coherence for CSA.

Updated Nationally Determined Contribution under the Paris Agreement (2020 -2030)	Building resilience and promoting livelihood opportunities for the youth and women in climate-vulnerable Agriculture landscapes and food systems	-the promotion of climate-smart agriculture. -Empowering youth and women in climate-vulnerable agricultural landscapes	-Reducing greenhouse gas emissions through various mitigation measures. -Promoting adaptation strategies in urban planning and infrastructure development. -Enhancing early warning systems for disaster risk management. -Investing in sustainable forest management and landscape restoration	-Inter-ministerial collaboration and coordination led by MESTI. -Mainstreaming climate change adaptation and mitigation strategies into existing national and sectoral plans. -Mobilizing financial resources from domestic, international, and private sectors.

Source: *Various policy documents*

Table 2: Performance Indicators and Outputs for Agricultural Programmes

Programme	**Main Outputs**	**Output Indicator**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Early Warning Systems and Emergency Preparedness	Level of infestation Of Fall Army Worm controlled	Area Recovered (Ha)			66,000	8,740	208,953	200,500
		Percent affected area recovered	100	100	100	100	100	100
	Enhanced surveillance and prevention of plant pests and diseases	Number of trained staff available to respond to plant pest and diseases emergencies	734	734	560	594	649	650
Mechanization, Irrigation and Water Management	Irrigation schemes developed	Area developed (ha)	13,009	14,934	16,908.85	16,908.85	21,283.85**	31,283.85*

Production and Productivity Improvement	Farmers reached with Improved technologies	Number of improved technologies disseminated			1,721	1,366	2,457	2,700*
		Number of Climate Smart Agricultural practices disseminated	1,296	1,465	1,170	987	1,695	1,780*
		Number of farm & home visits			507,743	404,150	669,595	676,291*
		Number of field demonstrations established				19,366	4,475	5,172**
		Number of training organized for farmer groups and FBOs	6082	4,003	4,203**	5,718	3,952	4,465**
Climate Change Resilience and Mitigation	Human resource capacity improved	Number of agriculture staff trained on climate change adaptation and mitigation	60	20	130	225	175	250**
	Institutional support system and mechanisms enhanced	Number of Ministerial Climate Change Task Force meetings	2	3	1	2	1	4**
	Risk reduction and transfer and Alternative livelihoods promoted	Number of farmers adopting diversified cropping systems	60	20	825	15,025	20,331	10,000**
		Number of Participatory Scenario Planning sessions undertaken	2	3	3	1	1	4**
		Number of farmers introduced to alternativelivelihoods	60	20	-	-	700	200**

Source: Various policy documents

**Indicative*

***Budget year*

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