# CLIMATE-SMART AGRICULTURAL PRACTICES AND GENDER-DIFFERENTIATED FOOD-NUTRITION OUTCOMES: EMPIRICAL EVIDENCE FROM RURAL SOUTH AFRICA


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# Climate-Smart Agricultural Practices and Gender-Differentiated Food-Nutrition Outcomes: Empirical Evidence from Rural South Africa

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**Abstract**

Climate change significantly impacts rural households' dietary outcomes by reducing farm productivity and income, prompting farmers to adopt climate-smart agricultural practices (CSAP) to mitigate adverse effects. This study examines the impact of CSAP adoption on gender-differentiated food security outcomes proxied by the Household Food Insecurity Access Scale (HFIAS) and household dietary diversity score (HDDS) in rural South Africa. Using nationally representative survey data from a baseline assessment conducted in 2023 through the ClimapAfrica Programme, we employed a Multinomial Endogenous Switching Regression (MESR) model to address selection bias and estimate the effects of CSAP adoption on gender-differentiated HFIAS and HDDS. Results show that male-headed households (MHHs) exhibited lower HFIAS scores (11.25) and higher HDDS (9.22) than female-headed households (FHHs), indicating that FHHs experienced greater food insecurity and less dietary diversity. These differences are attributed to gender-based disparities in access to resources such as land, credit, and extension services, education, and off-farm income opportunities. Furthermore, CSAP adoption patterns vary significantly by gender, with MHHs more likely to fully adopt CSAPs (21%) compared to FHHs (11%), while FHHs exhibit higher rates of single adoption (28%) and non-adoption (15%). Additionally, factors influencing CSAP adoption include farm size, cooperative membership, education, and access to credit, with gender-specific variations. Notably, full CSAP adoption positively impacted HDDS and reduced HFIAS across genders, with MHHs experiencing greater gains. Partial and single adoptions also enhance dietary outcomes, albeit to a lesser extent, with MHHs benefiting more from partial adoption due to higher off-farm income and agricultural diversification. The results highlight that while CSAP adoption significantly improves food security, persistent gender disparities highlight the need for targeted interventions that enhance resource access and opportunities for FHHs, thereby fostering greater resilience and sustainable agricultural productivity under changing climatic conditions.

**Keywords:** Endogenous switching; Food-nutrition; Gender-disaggregation; Livelihoods; Sustainability

# 1 Introduction

In sub-Saharan Africa (SSA), over 200 million households experience food and nutritional insecurity as a prominent characteristic of the inadequacy of the agricultural sector (FAO, 2021; Omotoso & Omotayo, 2024c). Despite the region's heavy reliance on agriculture for livelihoods and sustenance, productivity remains low due to factors such as climate variability, land degradation, limited access to modern farming technologies, and weak market linkages (Maindi et al., 2020; WFP, 2021). Notably, climate change poses a significant threat to agricultural productivity and food security outcomes, particularly in South Africa, where smallholder farming is the primary livelihood for millions (Mutengwa et al., 2023). Smallholder farmers, who constitute the majority of agricultural producers in the country, often struggle with poor soil fertility and limited access to financial and extension services in addition to climate change impacts (Atta-Aidoo et al., 2022; Maindi et al., 2020; Mutea et al., 2020).

Additionally, gender disparities in resource ownership and decision-making further exacerbate the vulnerability of women-led farming households to food insecurity (Atta-Aidoo et al., 2022; Gwara et al., 2022). These challenges highlight the urgent need for sustainable agricultural innovations, such as Climate-Smart Agricultural Practices (CSAP), to enhance resilience, improve productivity, and ensure equitable food security (FS) outcomes across different demographic groups (FAO, 2021; Outhwaite et al., 2022). Interestingly, CSAP encompasses practices such as conservation agriculture, agroforestry, water-efficient irrigation, and improved seed varieties, which help mitigate the adverse effects of climate variability (FAO, 2021; Fusco et al., 2020). While CSAP adoption has been widely promoted, empirical evidence remains limited on how its benefits vary across gender lines, particularly for food and nutrition security outcomes.

Intriguingly, gender plays a crucial role in shaping access to and adoption of agricultural technologies (Omotayo & Omotoso, 2025; Robinson, 2020). Women in rural South Africa face structural barriers, including limited access to land, credit, extension services, and decision-making power, which could affect their ability to adopt and benefit from CSAP (Danso-Abbeam et al., 2018). Despite these challenges, women are often responsible for household nutrition (Issahaku & Abdulai, 2020; Mirzabaev et al., 2023; Suyani et al., 2023), making it essential to understand whether CSAP adoption enhances food security equally for male- and female-headed households.

Nevertheless, the extent to which the CSAP has achieved the intended outcomes in terms of nutrition and food security of rural farmers remains uncertain (Merga et al., 2023; Outhwaite et al., 2022).

However, much of the existing research treats CSAP adoption as a household-level decision, overlooking intra-household differences in resource allocation, labour contribution, and nutritional outcomes. The implementation of CSAP has the potential to enhance agricultural productivity and FS outcomes in rural South Africa, despite climatic variability, by increasing agricultural revenue through increased crop yields or reduced production costs (Dechezleprêtre et al., 2022; Tilahun et al., 2023). Nevertheless, rural farmers encountered a range of CSAP methods that could be used concurrently, resulting in complementary outcomes (Robinson, 2020; WFP, 2021). The use of a variety of CSAP would assist rural farmers in enhancing productivity and FS despite the presence of several challenges, including inadequate resources and gender labour force (FAO, 2021). Gender disparities in FS have been a persistent characteristic of rural families, and the examination of this issue in the context of climate change has not been adequately established. The issue of gender inequality in FS is expected to be exacerbated by climatic change (Davis-Reddy, 2018; FAO, 2021). Notably, female-headed households in rural South Africa are considered the most susceptible to the adverse effects of climate change due to the institutional and structural weaknesses restricting their capacity to adopt modern technology (Abegaz et al., 2023; Outhwaite et al., 2022; Sikka et al., 2018). As a result, an increasing and significant body of literature has emerged regarding the adoption and effects of combining CSAP on rural household food-nutrition security outcomes (Danso-Abbeam et al., 2018; WFP, 2021).

Several studies (Davis-Reddy, 2018; FAO, 2021; Outhwaite et al., 2022), have shown that the use of CSAP would enhance soil fertility and facilitate adaptation to local climate change but often fail to differentiate between full, partial, and single adoption levels, treating CSAP adoption as a binary variable. This oversimplification overlooks how varying degrees of adoption influence food-nutrition security differently for men and women in rural South Africa. Gender-specific barriers, such as land tenure insecurity, limited access to credit, and labour constraints, further affect adoption choices, yet their impact on nutritional outcomes remains underexplored. Understanding whether partial or single adoption provides meaningful food security benefits compared to full adoption is crucial for designing effective interventions.

While research (Ahmed et al., 2023; Outhwaite et al., 2022; Tilahun et al., 2023), highlights CSAP's potential for improving agricultural productivity, there is limited empirical evidence on how different adoption levels influence dietary diversity, household food access, and nutrition resilience over time. Additionally, most studies (Brenya et al., 2024; Danso-Abbeam et al., 2018; Outhwaite et al., 2022) rely on cross-sectional data, making it difficult to assess whether full adoption leads to sustained improvements in nutrition compared to partial or single adoption. Thus, empirical research that examines gender disparities in dietary diversity and nutritional intake specifically among rural male- and female-headed farming households, as well as the influence of CSAP on these disparities, would add significantly to the ongoing policy discussions around this issue. A more nuanced understanding of these issues will help create targeted interventions that enhance both gender equity and a sustainable food system in rural South Africa.

## 2 Research Issue

### 2.1 Climate-smart agriculture and food security in the Southern African Development Community (SADC) region

The unpredictability of the climate and the occurrence of severe weather events in the SADC region, such as floods, droughts, and excessive rainfall, are among the primary threats to agricultural output and food security of rural households (Atta-Aidoo et al., 2022; Tekeste, 2021). Intriguingly, the SADC region, with 27%, is the second-largest producer of agricultural-related GHG emissions in SSA, after East Africa (34%), thereby calling for climate-smart farming (Omotoso & Omotayo, 2024c). Given that her agricultural sector is mostly sensitive to climatic extremes, climate change affects all four dimensions of food security, such as availability, accessibility, usage, and stability (Abegaz et al., 2023; Wassmann et al., 2019). It is essential to keep in mind that the issue of food security is a more complicated one. A wide variety of factors, including climate change, poverty, unequal distribution of natural resources, inadequate infrastructure, markets and financial resources, as well as gender inequity within countries, all play a significant role in determining food security (Abegaz et al., 2023; Maindi et al., 2020)

Despite this fact, climate change will operate as a multiplier of current concerns to rural households' food security (Abegaz et al., 2023). Accordingly, (Maindi et al., 2020; Tilahun et al., 2023) posited that due to their high sensitivity to the agricultural sector, vulnerable groups in SADC, such as rural women, children, the elderly, and people with disabilities, would be more severely affected by climate change than other groups, leading to a shortage of food supply. Likewise, the proportional economic cost of mitigating the extreme impact of climate on rural food-nutrition security may, in the worst cases, amount to 10% of the GDPs of developing countries in this region (Abegaz et al., 2023). The most severe consequences are projected to be felt by fisheries and rain-fed crop farming, resulting in a total annual loss of about USD 2,590 million by 2040 (Abegaz et al., 2023). For example, Namibia and Zambia may incur an annual loss of about 14% of their GDP if rural agricultural productivity were to decline; this will also lead to inadequate food supply, accessibility, nutrition, and sustainability (Akpan & Zikos, 2023; Batisani et al., 2021). Consequently, climate change's uncertain impacts on food supply and security mean inflated food costs are anticipated. This issue will probably become worse owing to increased food consumption brought on by population growth, fast urbanization, and poor income inequalities in emerging countries in SADC (FAO, 2021; Robinson, 2020).

## 2.2 Stylized facts on climate change and food security in rural South Africa

The synergy among climate change, productivity, and food security of rural farmers has become an intriguing research focus (FAO, 2021). Scholars (Mirzabaev et al., 2023; Robinson, 2020; Suyani et al., 2023), reported that climate change would exacerbate multidimensional poverty and severely impact food security (FS) in SSA nations, particularly in rural South Africa. A substantial body of literature (Omotoso & Omotayo, 2024b; Outhwaite et al., 2022) documents that climate change is intensifying weather variability in rural South Africa, with more frequent droughts and extreme rainfall events undermining agricultural productivity and exacerbating food insecurity. These climatic shifts have led to reduced crop yields, increased production risks, and heightened vulnerability among rural households that depend on rain-fed agriculture (Lal, 2020; Outhwaite et al., 2022). Moreover, (Mutengwa et al., 2023; WFP, 2021), emphasizes that food security in these regions is not solely a function of agricultural output but is intricately linked with climatic and socio-economic factors such as poverty, market access, and resource availability.

Empirical studies (Mutengwa et al., 2023; Omotoso et al., 2024) in rural South Africa reveal that average temperatures have risen by approximately 1°C since the mid-20th century, while rainfall variability has increased by 20–30%, intensifying drought conditions and adversely affecting crop yields. For instance, research (Harper et al., 2023; Omotayo & Omotoso, 2025; Wassmann et al., 2019) shows that smallholder farmers, who make up over 70% of rural agricultural production, experience yield reductions of up to 50% during severe drought years, leading to food insecurity levels that sometimes exceed 50% in affected areas.

Furthermore, (Harper et al., 2023; Omotayo & Omotoso, 2025; Wassmann et al., 2019) highlights stark gender disparities in household food security due to climate change. Consequently, female-headed households (FHHs) are empirically found to experience food insecurity rates that are 10–15 percentage points higher than those of male-headed households (MHHs), largely due to limited access to resources like land, credit, and extension services exacerbated by climate change. While climate-smart agricultural practices (CSAPs) offer a promising solution by potentially boosting yields by 15–20% (Atta-Aidoo et al., 2022; Su et al., 2023; Tilahun et al., 2023), their uneven adoption, especially among female-headed households, highlights the urgent need for targeted, inclusive policies that address both climate adaptation and resource disparities to enhance food security and resilience in rural communities.

Correspondingly, South Africa faces two critical environmental challenges that directly impact its agricultural sector and food security: (i) the need to increase agricultural output to meet the demands of a rapidly growing population, projected to reach 100 million by 2050, without compromising the well-being of rural farmers, and (ii) the urgent need to enhance the resilience of the region's agri-food systems to both current and anticipated climate change effects (Omotoso et al., 2024; Tilahun et al., 2023). Addressing these challenges requires sustainable solutions that not only boost productivity but also ensure equitable food and nutrition security outcomes, particularly for vulnerable rural households. These stylized facts underscore the urgent need for targeted policies that address both adaptation and resource disparities, ensuring that vulnerable rural communities can build resilience against the ongoing impacts of climate change on food security.

## 2.3 Theoretical and Conceptual Framework

The research adopted the utility theory to investigate the various benefits of rural farmers' adoption of CSAP on production, as well as how these effects decrease vulnerability and improve FNS outcomes. Utility theory is a concept within economics or decision theory that seeks to explain and quantify how individuals make choices among different alternatives based on their preferences and the satisfaction derived from those choices (Atta-Aidoo et al., 2022). Individuals seek to maximize their total utility subject to constraints such as income, prices, budgetary limitations, and options; thus, rational decision-makers will allocate their resources in such a way as to achieve the highest possible level of utility given their preferences and constraints (Mutengwa et al., 2023; Tekeste, 2021).

The utility function represents a farmer's preferences in adopting CSAP, considering the expected benefits, costs, and risks associated with conventional agricultural practices. CSAP aims to mitigate greenhouse gas (GHG) emissions from agricultural activities, enhance adaptation to climate change, and promote sustainable increases in productivity (Omotoso & Omotayo, 2024a). The conceptual framework (Figure 1) illustrates the CSAP adoption decision, emphasizing the influence of rural farmers' socioeconomic characteristics on their adoption choices and the resulting impact on food and nutrition security. These socioeconomic attributes play a crucial role in shaping adoption behaviour, particularly in the acceptance and implementation of new technologies, practices, or innovations (Atta-Aidoo et al., 2022). As shown in Figure 1, the framework underscores how integrating CSAP objectives can improve food security among farmers, strengthening resilience to climate change in rural South Africa.

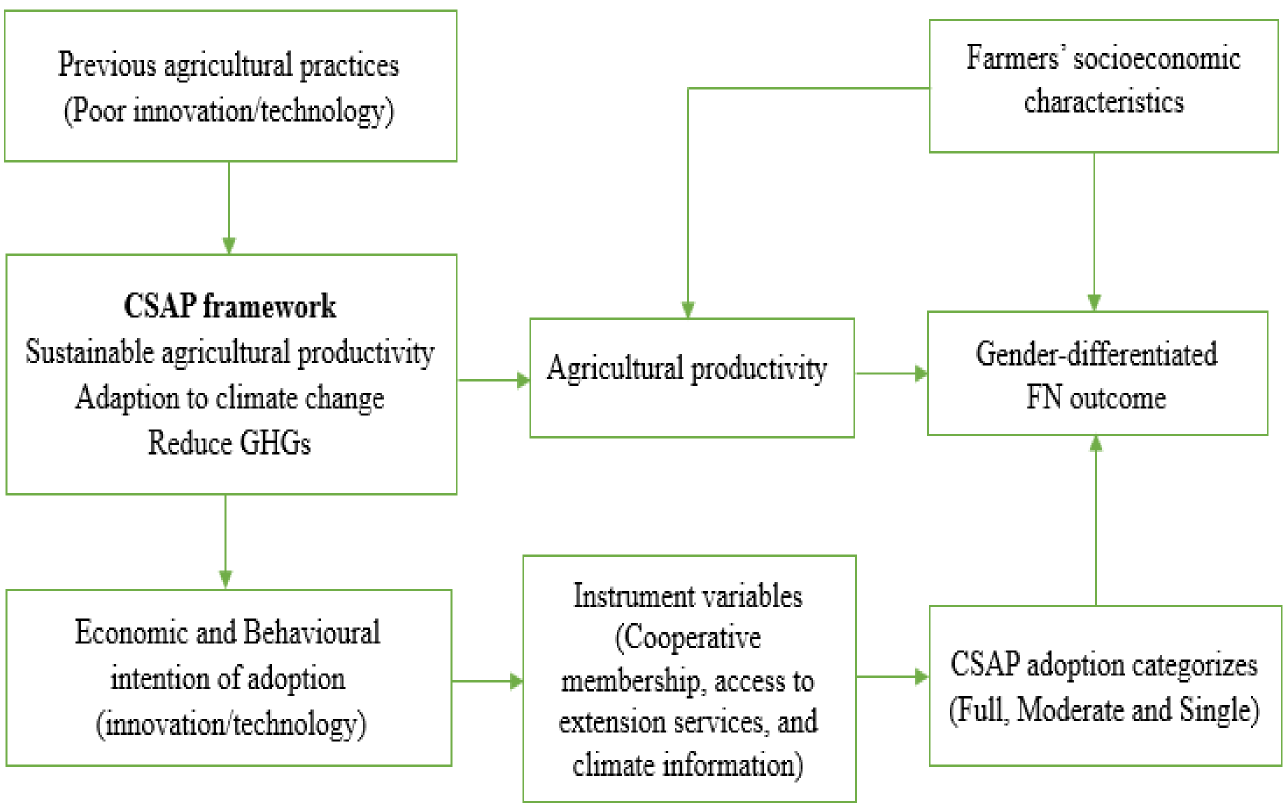


**Fig. 1.** Framework of the adoption impacts of Climate-Smart Agricultural Practices

Nevertheless, this study adds to the body of knowledge in two ways: First, our research is the first in the Southern African Development Community (SADC) to directly link the adoption of CSAP to FNS using nationally representative survey data. Notably, studying CSAP and gender-differentiated food-nutrition outcomes across the provinces of rural South Africa is crucial for developing resilient agricultural systems and improving food-nutrition security (FNS). This is essential for effectively mainstreaming climate-smart agricultural policies. Secondly, our multi-level analysis, which integrates endogenous switching regression (ESR) and average treatment effects methodologies, enables us to identify the most vulnerable rural households across the rural South African provinces, allowing for targeted rural food-nutrition policies. Furthermore, with food insecurity remaining a persistent challenge in many SSA countries, particularly in rural South Africa, enhancing the nutrition sensitivity of CSAP and food systems is a crucial area for both research and policy interventions.

## 3 Research Methodology

### 3.1 Study area description

The study was conducted in South Africa, focusing on six of the country's nine provinces: North-West, Free State, Mpumalanga, Limpopo, KwaZulu-Natal, and Eastern Cape, which represent a significant portion of the country's agricultural diversity. These provinces are predominantly inhabited by smallholder farmers who rely heavily on food crop farming and livestock farming for livelihoods (Omotayo & Omotoso, 2025). Farming activities are shaped by varying climates, ranging from semi-arid conditions to subtropical and temperate zones, influencing the types of crops and livestock reared. This agricultural dependence highlights the critical role of these provinces in sustaining rural livelihoods and food security of South Africa.

North-West province spans 104,882 km² of landmass, characterized by flat plains and bushveld vegetation (Mutengwa et al., 2023). It has a semi-arid climate with erratic rainfall (300–600 mm) and hot summers, and key crops grown include maize, sunflowers, and sorghum, with significant cattle grazing and game farming (Omotoso et al., 2024). This province is typified by savanna and grassland ecosystems ideal for rain-fed maize and livestock production. Yet, many rural communities here face persistent poverty and limited access to essential services, making them highly susceptible to climate variability, including erratic rainfall and drought (Rosenstock et al., 2019). These factors compromise agricultural reliability and food security, making North-West a key area for studying the impacts of climate and socio-economic constraints.

Covering a land area of 129,825 km², the Free State's agricultural productivity is crucial to South Africa's food security (Mutengwa et al., 2023). The province is predominantly characterized by grassland vegetation that supports extensive grain production and cattle farming (Omotayo et al., 2021). While it serves as a major agricultural hub, many of its rural areas still suffer from infrastructural deficits, high poverty rates, and vulnerability to climate extremes, particularly droughts and heatwaves (Mutengwa et al., 2023). These factors contribute to fluctuating agricultural outputs and food insecurity, justifying their inclusion in a comparative analysis of rural resilience. Its continental climate has hot summers, cold winters, and summer rainfall (500–750 mm), with vegetation dominated by grasslands, transitioning to savanna in drier western parts. The province is a leading producer of maize, wheat, and sunflowers, with substantial sheep and cattle farming (Mutengwa et al., 2023; Omotoso et al., 2024)

Furthermore, Mpumalanga spans a 76,495 km² landmass and boasts diverse landscapes, from lowveld savannah to highveld grasslands and escarpment forests (Rosenstock et al., 2019). The climate ranges from subtropical in the lowveld to cooler highveld regions, with summer rainfall (500–1,500 mm). In Mpumalanga, a blend of highveld grasslands and bushveld supports a mixed agricultural economy that includes crop farming, livestock rearing, and forestry. Despite its economic contributions, rural areas in the province confront pockets of poverty and food insecurity, with climate change events such as droughts and heavy rains posing significant challenges (Mutengwa et al., 2023). This complexity provides valuable insights into how climate change and economic disparities interact to influence agricultural productivity and food security. Crops grown include citrus, sugarcane, bananas, maize, and wheat, alongside forestry activities; vegetation varies from thornveld in dry areas to montane forests on the escarpment (Omotoso et al., 2024)

Limpopo is the fourth province selected, covering 125,754 km², featuring plains, valleys, and mountain ranges like the Soutpansberg (Rosenstock et al., 2019). Its climate is semi-arid to subtropical, with rainfall varying from 200 mm in the west to over 1,000 mm in the east (Harper et al., 2023). Limpopo’s landscape is dominated by dry bushveld, savanna, and arid vegetation, with many areas experiencing low and highly variable rainfall (Harper et al., 2023). Predominantly, Limpopo faces high poverty and acute food insecurity exacerbated by climate change impacts like prolonged droughts and rising temperatures (Tilahun et al., 2023). This vulnerability underscores the need for targeted studies on adaptation and resilience in resource-poor settings. Key crops include tropical fruits, nuts, and maize, complemented by cattle farming.

KwaZulu-Natal spans across 94,361 km² of land area, with coastal plains, midlands, and the Drakensberg Mountains. Its climate is humid and subtropical along the coast, cooler and wetter in higher altitudes, with over 1,000 mm of annual rainfall (Harper et al., 2023). KwaZulu-Natal boasts diverse vegetation from coastal forests and subtropical wetlands to inland savannas that supports a vibrant agricultural (Harper et al., 2023). However, rural regions in the province still grapple with poverty, resource access issues, and climate-induced disruptions such as flooding and erratic rainfall, which compromise food security (Omotayo et al., 2021). Diversity in both ecology and socioeconomics makes KwaZulu-Natal an essential province for integrated analysis. Sugarcane dominates the coast, while maize, vegetables, and fruits are grown inland, supported by livestock and forestry. Its diverse landscape supports agriculture, industry, and tourism.

The Eastern Cape covers 168,966 km² and has a varied landscape, including coastline, semi-arid Karoo, and mountain ranges (Rosenstock et al., 2019). Its coastal areas are temperate and wetter, while the inland Karoo is dry and semi-arid, with rainfall from 200 to 1,000 mm annually. Crops include citrus, maize, sorghum, and vegetables, with sheep and goat farming prevalent (Mutengwa et al., 2023). Its diverse climate and topography make it agriculturally versatile (Harper et al., 2023). The Eastern Cape features a mosaic of coastal thickets, grasslands, and indigenous forests, with vegetation that varies from moist coastal areas to arid inland regions (Harper et al., 2023). Economically, the province is marked by high rural poverty and a predominance of smallholder, subsistence agriculture (Mishra et al., 2021). Climate change has led to more erratic rainfall and increased drought frequency, which further undermines agricultural productivity and food security (Rosenstock et al., 2019), making the province a critical case for understanding the climate-food security nexus.

### 3.2 Source of data and collection

Data utilized in this study were derived from a broader baseline assessment study conducted in 2023 in the 9 provinces of South Africa through the climapAfrica programme, which was funded by DAAD (German Academic Exchange Service) in collaboration with the Department of

Agriculture, Forestry and Fisheries (DAFF) and North-West University, South Africa. Participants' demographics, food security and nutrition data, production, and CSAP adoption were all included in the data collection. Data were collected using a quantitative research procedure. A stratified random sampling technique was employed to select 1,180 smallholder farmers across the six provinces (North-West, Free State, Mpumalanga, Limpopo, KwaZulu-Natal, and Eastern Cape). Stratification ensured that farmers from different agroecological zones, socio-economic backgrounds, and farming practices were adequately represented.

### 3.3 Data analysis and estimation technique

#### *i. Measurement of household gender-differentiated food security (FS) outcomes*

Given the multidimensional nature of FS, this study employs two key household nutrition indicators: The Household Food Insecurity Access Scale (HFIAS) and the Household Dietary Diversity Score (HDDS). First, the HFIAS quantifies food insecurity by capturing behavioural and psychological dimensions related to food access (Kangogo et al., 2021). A household experiencing no food insecurity receives a minimum score of 0, indicating better food access. Conversely, a severely food-insecure household, characterized by frequent consumption of less preferred foods or meal skipping due to inadequate access, receives a maximum score of 27 (Outhwaite et al., 2022). The second indicator, HDDS, measures dietary quality by assessing the diversity of foods consumed by a household (Davis-Reddy, 2018; WFP, 2021). Food items consumed over a week are classified into twelve categories: cereals, tubers and roots, vegetables, fruits, meat and poultry, eggs, fish, pulses and nuts, legumes, milk and dairy products, oils and fats, sugar and honey, and miscellaneous items. HDDS serves as a robust predictor of household nutritional status (Abegaz et al., 2023; UNICEF, 2023)

#### *ii. CSAP adoption-decision and impact evaluation in gender-differentiated households*

Following the approach of Atta-Aidoo et al. (2022) and Tilahun et al. (2023), we utilized a random utility framework to model the household's decision regarding the adoption of CSAP, denoted as $Q_i$. This parameter represents the utility difference between adopting CSAP ($Q_{i1}$) and using conventional agricultural practices ($Q_{i0}$). When the benefits of adopting CSAP exceed those of conventional practices, rural farmers are inclined to adopt CSAP, i.e., $Q_{i1} - Q_{i0} > 0$. However, due to the unobservable nature of these two utilities, the net benefit (Qi) derived from adoption is a latent variable. This net benefit is determined by both observable and unobservable characteristics, as represented in equation (2).

$$Y_i = X_i\beta + \mu_i \quad \text{given that } Y_i = \begin{cases} 1\ if\ \text{Yi} > 0 \\ 0\ otherwise \end{cases} \tag{2}$$

Where Qi represents the adoption decision of CSAP in gender-differentiated households (1 = adopted; 0 = otherwise). The vector β contains the parameters to be estimated concerning food security (FS) outcomes. The vector X includes the socioeconomic and institutional characteristics of farmers that influence their adoption decisions. Farmers make technology adoption choices based on the information available to them, and adopters and non-adopters of CSAP are not randomly assigned to these groups, as they differ systematically. This necessitates addressing selectivity bias. To do so, we employ the Multinomial Endogenous Switching Regression (MESR) model and Average Treatment Effects (ATT) to estimate the effects. The combination of these two models enhances the estimates, as each model addresses unique restrictions that cannot be resolved independently (Atta-Aidoo et al., 2022; Tilahun et al., 2023).

### *i. Multinomial Endogenous Switching Regression (MESR) Model*

Bias stemming from both observable and unobservable variables may arise due to the endogenous self-selection of rural farmers into adoption and non-adoption groups (Atta-Aidoo et al., 2022; Mutea et al., 2020). In this study, a farmer's decision to adopt at least one CSAP in response to climate change is treated as a dummy variable (1 = adopter, 0 = non-adopter). Following the approach of Antwi-Agyei et al. (2021) and Mutengwa et al. (2023), we employ the Multinomial Endogenous Switching Regression (MESR) model to adjust for selection bias, using a logit model. The MESR framework consists of two phases. The first stage models the determinants of CSAP adoption in gender-differentiated rural households and addresses the unobserved variability through a logit model. The selection equation for the adoption decision is given as follows:

$$Y_i = X_i\beta + \mu_i \qquad \text{given that } M_i = \begin{cases} 1\ if\ \text{Yi} > 0 \\ 0\ otherwise \end{cases} \tag{3}$$

Where Yi is a binary variable indicating the adoption of CSAP (1 = adopted, 0 = non-adopted); β is a parameter vector to be estimated; X is a vector of socioeconomic and institutional characteristics of rural farmers that influence their adoption decisions, such as access to extension services, credit, and climate information; and $\mu$ is the random error term. The MESR model accounts for selectivity bias and estimates the impact of CSAP adoption on outcome variables by analyzing the interaction between the adoption decision (Yi) and explanatory variables (Antwi-Agyei et al., 2021). The second stage involves combining Ordinary Least Squares (OLS) regression with a selectivity correction term derived from the first stage. This is used to examine the relationship between household gender-differentiated outcome variables (HDDS and HFIAS) and explanatory factors, incorporating the CSAP adoption decision. The results are presented in Appendix Tables A2 and A3.

To improve identification and account for potential selection bias in CSAP adoption, access to extension services, access to climate information, and membership in farmer cooperatives were employed as selection instruments (Appendix Table A1). These variables were selected primarily because they provide farmers with information, knowledge, technical support, and opportunities that directly influence their capacity and propensity to adopt CSAP, while they are not expected to determine household FNS independently once household socioeconomic characteristics, farm characteristics, and other relevant covariates are controlled for. Access to extension services is expected to influence CSAP adoption through technology-specific information, demonstrations, training, and technical guidance. Extension contacts reduce information and skill constraints associated with the adoption of unfamiliar agricultural practices (Omotoso, 2026). Importantly, in the present identification strategy, extension access is not assumed to affect HDDS or HFIAS directly; rather, its hypothesized pathway to these outcomes operates through improved agricultural practices and farm production. Similarly, access to climate information is expected to influence FNS primarily by improving farmers' ability to anticipate and respond to climate risks through the adoption of appropriate CSAPs.

Consistently, membership in farmer cooperatives provides access to information, peer learning, collective training, input networks, and other institutional resources that would facilitate CSAP adoption (Akano et al., 2023; Omotayo & Omotoso, 2025). Consequently, the identifying assumption is that the remaining effect of cooperative membership on HDDS and HFIAS operates through CSAP adoption rather than through an independent pathway. We acknowledge that the exclusion restriction cannot be established solely on theoretical grounds because extension access, climate-information access, and cooperative membership may be correlated with unobserved household characteristics, including motivation, literacy, social networks, and infrastructure access. Therefore, the validity of the instruments was assessed empirically using falsification tests. The results reported in Appendix Table A1 showed that the instruments are statistically relevant to the CSAP adoption/selection equation, while the falsification results provide no evidence of a systematic direct association between the instruments and the outcome equations after conditioning on the included covariates. These findings provide empirical support for the exclusion restriction underlying the identification strategy.

The MESR model was estimated using full-information maximum likelihood (FIML), which jointly estimates the selection and outcome equations and accounts for potential correlation between their error terms. Robust standard errors were reported for the MESR parameters, while bootstrapped standard errors based on 1,000 replications were used in estimating the Average Treatment Effect on the Treated (ATT). Thus, the identification strategy combines theoretically motivated selection instruments, observable covariate adjustment, and falsification evidence to reduce concerns regarding selection bias and strengthen inference on the relationship between CSAP adoption and household food and nutrition security.

### *ii. Average Treatment and Heterogeneity Effects Estimation*

Average treatment effect (ATT) was employed to determine the impacts of combinatory adoptions of CSAP on outcome variables (gender-differentiated FS). Following the approach of Akano et al. (2023) and Atta-Aidoo et al. (2022), this method enables the creation of counterfactual outcomes for both adoption regimes (adopters and non-adopters). This allows for a comparison between the expected FNS outcomes (HDDS and HFIAS) of actual adopters and their counterfactual counterparts (non-adopters). The conditional expectations for FNS in the four scenarios are presented in equations and defined as follows:

$$E(y_{1i} l A_i = 1) = X_{1i}\beta_1 + \sigma_{1\eta}\lambda_{1i} \qquad \text{......................................} (4a)$$

$$E(y_{2i} l A_i = 0) = X_{2i}\beta_2 + \sigma_{2\eta}\lambda_{2i} \qquad \text{......................................} (4b)$$

$$E(y_{2i} l A_i = 1) = X_{1i}\beta_2 + \sigma_{2\eta}\lambda_{1i} \qquad \text{......................................} (4c)$$

$$E(y_{1i} l A_i = 0) = X_{2i}\beta_1 + \sigma_{1\eta}\lambda_{2i} \qquad \text{......................................} (4d)$$

$Y_{1i}$= Gender-differentiated FNS outcome if household $i$ adopts CSAP

$Y_{2i}$= Gender-differentiated FNS outcome if household $i$ does not adopt CSAP

$A_i = 1$= CSAP adopter.

$A_i = 0$= CSAP non-adopter

# 4 Results and discussion

## 4.1 Summary of descriptive variables

Climate change impacts rural households' dietary outcomes by reducing farm productivity and income (Ayodele et al., 2025; Harper et al., 2023). This compelled farmers to implement various CSAPs on their farms to mitigate climate change impacts. Farm productivity and income ultimately improve rural households' dietary outcomes, but improved farm income is dependent on the level of adoption of CSAPs (Mirzabaev et al., 2023). Appendix Table B1 reveals the variable description of policy variables employed in the study. Descriptive statistics in Table 1 and the variable description employed reveal pronounced gender disparities in food security, dietary diversity, and access to productive resources in South Africa. The HFIAS of the rural households (Table 1) revealed male-headed households (MHHs) with a mean of 11.25, indicating moderate food insecurity. The magnitude of this gap (approximately 4.5 points) is substantial and comparable to gender differentials reported in similar African contexts (Antwi-Agyei et al., 2021; Danso-Abbeam et al., 2018), suggesting that gendered constraints remain a major driver of food insecurity.

Contrarily, household dietary diversity score (HDDS) indicates higher dietary diversity among MHHs (mean = 9.22) relative to FHHs (mean = 8.36). Although the absolute difference appears modest, prior studies show that even a one-food-group difference in HDDS is nutritionally meaningful, particularly for micronutrient adequacy in rural diets (Atta-Aidoo et al., 2022; FAO, 2021). These outcome gaps are consistent with theoretical expectations from the gendered access-to-resources framework, which posits that disparities in land, income opportunities, climate information, and institutional support translate into unequal welfare outcomes (Issahaku & Abdulai, 2020; Mirzabaev et al., 2023). This highlights disparities in food access and diversity, suggesting MHHs are relatively better off in these aspects. Studies (Kangogo et al., 2021;

Wassmann et al., 2019) consistently show that MHHs tend to have better agricultural outcomes due to greater access to resources such as land, credit, and extension services.

Research (Kangogo et al., 2021; Outhwaite et al., 2022) emphasizes that FHHs are more likely to experience food insecurity due to lower income levels, limited resource access, and gendered roles in agriculture. As shown in Table 1, MHHs in South Africa derive income from a wider range of sources and are able to implement various combinations of CSAP. Notably, MHHs consistently generate more off-farm income from a broader portfolio of sources and diversify their agricultural activities more than their female counterparts, who tend to prioritize farming above all other pursuits. This diversification acts as a key mediating channel, enabling MHHs to smooth income, absorb climate shocks, and invest in CSAPs that enhance productivity and food availability. These patterns align with the observed HFIAS and HDDS outcomes, reinforcing the role of income and diversification as central pathways linking CSAP adoption to improved food and nutrition security.

Agricultural diversification captured through engagement in multiple enterprises such as crop production, livestock, poultry, and micro-livestock emerge as a particularly important mediator. As documented in the literature (Antwi-Agyei et al., 2021; Merga et al., 2023), diversification reduces production risk and stabilizes income, thereby facilitating investment in capital-intensive technologies such as CSAPs. In this study, higher diversification among MHHs is strongly associated with lower food insecurity and more stable food consumption, suggesting that diversification statistically explains a significant portion of the gender gap in food and nutrition outcomes. This finding is consistent with evidence that diversified farming systems enhance resilience to climate variability and protect household diets (Omotoso & Omotayo, 2026)

Regarding education status, majority of household heads (51.2% male and 78.0% female) are educated. Higher levels of education are indicative of robust human capital, which provides producers with the knowledge and skills required to make informed decisions regarding improved agricultural production practices (Kangogo et al., 2021). Enhanced agricultural practices would result in increased crop yields and enhanced income generation for rural farming households, thereby enhancing food security (Omotoso & Omotayo, 2024b). Furthermore, government extension services are accessible to majority of rural households. The adoption of agricultural technology and climate change adaptation strategies among rural farmers is significantly influenced by extension services (Atta-Aidoo et al., 2022; Omotayo et al., 2022)

Furthermore, access to critical services such as climate information, extension services, and credit facilities also shows significant gender-based differences. Subsequently, MHHs are more likely to access these resources, as indicated by significant t-test values for climate information ($t = 0.193$, $p<0.05$), extension services ($t = 0.223$, $p<0.1$), and credit facilities ($t = 0.192$, $p<0.01$). Similarly, MHHs have higher participation in cooperatives ($t = 0.117$, $p<0.05$) and greater agricultural diversification ($t = 0.099$, $p<0.01$), which may contribute to better productivity and resilience. The descriptive evidence suggests that gender disparities in food and nutrition outcomes are not merely the result of differences in CSAP adoption but are mediated through unequal access to income diversification opportunities, institutional support, and productive resources. The observed gender disparities underscore the need for targeted interventions to improve access to resources, services, and opportunities for female-headed households. Bridging these gaps would enhance food security, income, and agricultural productivity for disadvantaged households.

**Table 1.** Summary statistics of the outcome and selected interest variables (n= 1,180 rural households)

| Variables | Description | Male-headed households (MHHs) | | Female-headed households (FHHs) | | t-test |
|---|---|---|---|---|---|---|
| **Outcome variable** | | **Mean** | **Std. Dev.** | **Mean** | **Std. Dev.** | |
| Household Food Insecurity Access Score (HFIAS) | An absolutely food-secure HH receives a score of 0, while a completely food-insecure HH gets a score of 27. | 11.25 | 5.19 | 15.71 | 9.06 | -4.46*** |
| Household Dietary Diversity Score (HDDS) | Measured based on the intake of 12 food groups consumed by the HH | 9.22 | 4.03 | 8.36 | 7.14 | 0.86*** |
| Number of food groups | Measured by intake of food groups consumed by the HH | 7.71 | 2.69 | 6.35 | 3.47 | 1.36*** |
| **Selected interested variables** | | | | | | |
| Age | Actual age of household head (HH) | 48.7 | 18.05 | 45.21 | 20.87 | 3.49** |
| Income | Income from farm produce | 276,093.14 | 18,902.76 | 101,274.22 | 73,0565.11 | 174818.9* |
| Off-farm activities | Dummy; 1 if yes, 0 if otherwise | 0.727 | 0.219 | 0.663 | 0.554 | 0.064* |
| Household size | Total members of household member | 5.01 | 3.52 | 4.14 | 3.08 | 0.87*** |
| Farm size | Actual farm size in hectares (Continuous) | 6.82 | 4.01 | 3.75 | 1.98 | 3.07*** |
| Education status | Dummy; 1 if HH has formal education, 0 if otherwise | 0.512 | 0.431 | 0.780 | 0.211 | -0.268 |
| Marital status | Dummy; 1 if married, 0 if otherwise | 0.756 | 0.338 | 0.612 | 0.510 | 0.144 |
| Climate information | Dummy; 1 if yes, 0 if otherwise | 0.615 | 0.282 | 0.422 | 0.315 | 0.193** |
| Extension service | Dummy; 1 if yes, 0 if otherwise | 0.885 | 0.401 | 0.662 | 0.403 | 0.223* |
| Credit facilities | Dummy; 1 if yes, 0 if otherwise | 0.505 | 0.274 | 0.313 | 0.302 | 0.192*** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Member of cooperative | Dummy; 1 if yes, 0 if otherwise | 0.742 | 0.231 | 0.625 | 0.127 | 0.117** |
| Agricultural diversification | Dummy; 1 if yes 0 if otherwise | 0.721 | 0.512 | 0.622 | 0.451 | 0.099*** |
| Information from Radio | Dummy; 1 if yes 0 if otherwise | 0.625 | 0.365 | 0.590 | 0.502 | 0.035** |
| Community meetings | Dummy; 1 if yes 0 if otherwise | 0.751 | 0.218 | 0.802 | 0.196 | -0.051* |
| Social safety net | Dummy; 1 if access to government programs such as cash transfers, input subsidies, 0 if otherwise | 0.603 | 0.425 | 0.724 | 0.382 | -0.121** |
| **Number of observations** | | 721 | | 459 | | |

**Note:** ***p<0.01, **p<0.05, *p<0.1

## 4.2 Typologies of CSA practices adopted by smallholder farmers

Table 2 highlights the adoption levels of CSAP among farming households, categorizing them into four distinct groups: full adoption, partial adoption, single adoption, and non-adoption. The adoption patterns reveal significant differences between male-headed and female-headed households, as shown by the t-test values. Full adoption, which involves implementing soil and water conservation, improved seed varieties, and irrigation, was more common among MHHs (21%) compared to FHHs (11%). The significant difference ($t = 0.10$, $p<0.01$) suggests that MHHs are better positioned to adopt all recommended CSAPs comprehensively. Partial adoption, where households implement two CSAP combinations, was observed more in male-headed households (55%) than FHHs (46%), with a smaller but significant difference ($t = 0.09$, $p<0.1$).

Contrarily, single adoption, which involves adopting only one CSAP, was significantly higher among FHHs (28%) than MHHs (17%). This reflects potential resource constraints or accessibility challenges for FHHs, which limit their ability to adopt multiple practices. Non-adoption, characterized by households failing to implement any CSAP, was also notably higher among FHHs (15%) compared to MHHs (7%) ($t = -0.08$, $p<0.05$). These differences highlight gender-specific challenges in adopting climate-smart agricultural solutions, including access to resources, extension services, and education (Baiyegunhi et al., 2022; Outhwaite et al., 2022). Targeted interventions addressing these disparities would enhance CSAP adoption rates, especially for FHHs, ultimately promoting sustainable farming and climate resilience.

Consequently, Appendix Table A4 presents the typologies of CSAP adopted by smallholder farmers based on combinations of soil and water conservation (S), improved seed varieties (V), and irrigation technology (I) in South Africa. A significant number (18.05%) of smallholder farmers are non-adopters of CSAP, highlighting significant barriers to adoption such as limited access to information, resources, and technical support. Conversely, the combination of soil and water conservation and irrigation is the most common adoption pattern (22.88%) in South Africa, reflecting the foundational importance of these practices for sustainable farming. The high adoption rate of irrigation solely or combined, highlights its importance in climate adaptation. Additionally, 6.53% of farmers adopt all three CSAP, suggesting that resource constraints, lack of knowledge, or inadequate extension services could be preventing farmers from fully integrating CSAP in farming operations in South Africa. Notably, the adoption of CSAP like soil conservation and drought-resistant seeds directly enhances farmers' ability to cope with climate variability, thus improving productivity and better food-secured households (Mutengwa et al., 2023; Omotoso et al., 2024).

Notably, farmers' comprehension of climate change has a major influence on their degree of adaptation and the actions they take to mitigate the effects of climate change on their outputs (Baiyegunhi et al., 2022). The result suggests that majority of rural farmers are cognizant of local climatic variations and are thus able to make informed decisions on adaptations to deal with climate change and its impact on their farms. This discovery is consistent with the assertions of (Mutengwa et al., 2023; Sikka et al., 2018) who contended that the significance of CSAP in SSA is not sufficiently highlighted. The study suggests that this may be the cause of the moderate adoption. Increasing the adoption rates of these practices is crucial for achieving sustainable agricultural productivity under changing climatic conditions.

**Table 2.** Adoption categorizes of CSAP among rural farmers

| **CSAP adoption** | | **Male HH** | | **Female HH** | | **t-test** |
|---|---|---|---|---|---|---|
| | | **Mean** | **Std. Dev.** | **Mean** | **Std. Dev.** | |
| Full adoption | Adopted all the identified CSAP (Soil and water conservation, improved seed varieties, and irrigation) in farming operations | 0.21 | 0.37 | 0.11 | 0.10 | 0.10*** |
| Moderate adoption | Adopted any 2 combinations of CSAP in the farming operation | 0.55 | 0.34 | 0.46 | 0.29 | 0.09* |
| Single adoption | Adopted only CSAP in the farming operation | 0.17 | 0.08 | 0.28 | 0.12 | -0.11** |
| Non-adopter | Failed to adopt any CSAP in the farming operation | 0.07 | 0.04 | 0.15 | 0.11 | -0.08** |

**Note:** ***p<0.01, **p<0.05, *p<0.1

### 4.3 Parameter estimates of the determinants of CSAP adoption categories – Multinomial Logit

Table 3 reports the first-stage results from the multinomial logit model, which estimates the determinants of climate-smart agricultural practice (CSAP) adoption across gender-differentiated rural households (male-headed and female-headed) in South Africa. This stage identifies the factors influencing households' selection into different CSAP adoption categories (non-adoption, single, moderate, and full adoption). Building on these results, the second stage examines the welfare implications of CSAP adoption. Specifically, Appendix Tables A2 and A3 present the gender-differentiated impacts of CSAP adoption on food and nutrition outcomes, measured by household dietary diversity score (HDDS) and household food insecurity access score (HFIAS), respectively. Together, the two-stage framework allows for an integrated assessment of both the drivers of CSAP adoption and their implications for food and nutrition security among rural households in South Africa.

Notably, using non-adopters as the reference category, the model estimates marginal effects (ME) for single, moderate, and full adoption of CSAP (Table 3), allowing for a nuanced assessment of adoption intensity and gender-specific decision-making pathways. The results reveal pronounced gender-specific heterogeneity in both the magnitude and direction of the determinants across adoption bundles. For full adoption of CSAP, farm size emerges as a key driver among male-headed households (MHHs). A one-unit increase in farm size increases the probability of full adoption by 1.4 percentage points ($\beta = 0.014$, $p < 0.01$), highlighting the role of land endowments in facilitating the uptake of multiple, often complementary, CSAPs. Membership in farmer cooperatives also raises the likelihood of full adoption among MHHs ($\beta = 0.027$, $p < 0.10$), reflecting the importance of collective action in improving access to information, inputs, and markets. Additionally, access to social safety nets significantly increases the probability of full adoption ($\beta = 0.037$, $p < 0.05$), suggesting that risk-buffering mechanisms relax liquidity and risk constraints associated with adopting comprehensive CSAP.

The study conforms with (Danso-Abbeam et al., 2018; Wassmann et al., 2019), who reported that membership in cooperative societies and large farm size are highlighted as key factors influencing farmers' ability to understand and implement multiple CSAP technologies. Literate and trained farmers are more likely to adopt improved seeds and integrated practices in SSA (Davis-Reddy, 2018; Omotoso & Omotayo, 2026). Contrarily, education is the dominant determinant of full adoption among female-headed households (FHHs). Educated FHHs are 10% more likely to fully adopt CSAP ($\beta = 0.100$, $p < 0.01$), a relatively large effect size compared with other covariates. This underscores the central role of human capital in overcoming informational and managerial barriers faced by women farmers. This finding is consistent with prior evidence that education enhances farmers' capacity to understand, combine, and manage complex agricultural technologies (Atta-Aidoo et al., 2022; Maindi et al., 2020). However, access to credit has a negative and significant effect on full adoption among FHHs ($\beta = -0.032$, $p < 0.10$), suggesting that credit constraints not only reflect access but also the burden of repayment obligations, intra-household demands, or limited control over loan utilization. This highlights that credit access alone does not guarantee technology scaling for women without complementary institutional and social support.

For moderate adoption of CSAP, determinants differ markedly by gender. Among MHHs, engagement in off-farm activities significantly increases the likelihood of moderate adoption ($\beta = 0.099$, $p < 0.01$). This relatively large marginal effect suggests that supplementary income enables households to selectively adopt certain CSAPs without committing to the full adoption package. This aligns with (Omotoso & Omotayo, 2024b; Robinson, 2020), who posited that off-farm income relaxes financial constraints and encourages experimentation with new technologies. Conversely, farm size and farming experience negatively affect moderate adoption among MHHs, indicating that larger and more experienced farmers tend to move directly toward full adoption rather than incremental uptake. Among FHHs, moderate adoption is negatively associated with access to credit, reinforcing the earlier result that financial obligations and competing household responsibilities could constrain women's ability to scale beyond limited adoption. These findings suggest that moderate adoption among FHHs may represent a constrained equilibrium rather than a transitional stage toward full adoption.

For single adoption of CSAP, the results indicate that MHHs with greater farming experience ($\beta = 0.020$, $p < 0.01$) and larger farm sizes ($\beta = 0.044$, $p < 0.01$) are more likely to adopt individual CSAPs. This pattern suggests strategic selectivity, where experienced farmers prioritize specific practices that address immediate production or climate risks. Cooperative membership further enhances adoption by improving access to inputs, credit, and markets, consistent with findings from Baiyegunhi et al. (2022) and Rosenstock et al. (2019). Among FHHs, household size positively influences single adoption, reflecting the importance of labour availability in implementing individual CSAPs. Unlike full and partial adoption, access to credit has a positive effect on single adoption among FHHs, indicating that small-scale or targeted financial support could enable women farmers to implement specific practices even if broader adoption remains constrained. This result aligns with (Antwi-Agyei et al., 2021; Gwara et al., 2022), who document persistent gender gaps in access to productive resources that limit women's ability to adopt comprehensive CSA packages. Cooperatives facilitate member access to inputs, credit, and markets (Baiyegunhi et al., 2022; Rosenstock et al., 2019). Previous studies (Mutengwa et al., 2023; Sikka et al., 2018) have shown that access to finance elevates the likelihood of rural families adopting improved agricultural technologies.

However, access to climate information consistently increases the likelihood of CSAP adoption across all categories and both gender groups, corroborating earlier studies (Omotayo & Omotoso, 2025; Tilahun et al., 2023). Similarly, (Baiyegunhi et al., 2022; Suyani et al., 2023) have shown that rural families' access to climatic information significantly affects their likelihood of adopting agricultural technology. This research consistently found a beneficial impact of access to climatic information on the adoption of CSAP practices in South Africa. The positive effect likely reflects improved awareness, risk perception, and timely decision-making facilitated by extension agents and media channels. While potential endogeneity in access to information cannot be fully ruled out, the results highlight its central role as a catalyst for CSAP uptake. Notably, the results reveal clear gender-differentiated adoption pathways. Adoption decisions among MHHs are primarily mediated by resource endowments and income diversification.

The FAO highlights persistent gender disparities in access to agricultural inputs and resources, which limit women's ability to adopt certain CSA technologies (FAO, 2021; Segbefia et al., 2023). Notably, farm size, off-farm income, and cooperative membership facilitate progression toward full adoption. In contrast, FHHs' adoption behaviour is more strongly shaped by human capital, social protection, and constrained access to finance, with credit playing a dual role that enables limited adoption but hinders scaling. These findings underscore the need for gender-sensitive CSA policies that combine education, tailored credit instruments, labor-saving technologies, and strengthened extension services to enable women farmers to move beyond marginal adoption toward full participation in climate-smart agriculture.

**Table 3**. Multinomial logit model – Parameter estimates of gender-differentiated CSAP adoption categorizes

| **Variables** | **Full adoption** | | **Moderate adoption** | | **Single adoption** | |
|---|---|---|---|---|---|---|
| | **Male HH** | **Female HH** | **Male HH** | **Female HH** | **Male HH** | **Female HH** |
| | **M.E** | **M.E** | **M.E** | **M.E** | **M.E** | **M.E** |
| Age | 0.001* | 0.000 | 0.001 | -0.000 | -0.001 | -0.000 |
| | (0.001) | (0.001) | (0.001) | (0.001) | (0.001) | (0.001) |
| Income | 0.009 | -0.060*** | 0.107*** | -0.000 | -0.057** | -0.013 |
| | (0.014) | (0.016) | (0.024) | (0.020) | (0.027) | (0.017) |
| Married | -0.011 | -0.022 | -0.014 | -0.068*** | 0.116*** | 0.001 |
| | (0.015) | (0.018) | (0.023) | (0.018) | (0.030) | (0.018) |
| Educational dummy | 0.019 | 0.100*** | -0.130*** | -0.012 | -0.010 | 0.097*** |
| | (0.019) | (0.028) | (0.034) | (0.027) | (0.033) | (0.029) |
| Household size | 0.001 | -0.002 | -0.010* | -0.003 | -0.001 | 0.016*** |
| | (0.004) | (0.004) | (0.006) | (0.004) | (0.006) | (0.004) |
| Farming experience | 0.005 | 0.006** | -0.020*** | -0.004 | 0.020*** | -0.004 |
| | (0.003) | (0.003) | (0.007) | (0.004) | (0.006) | (0.005) |
| Farm size | 0.014** | 0.015* | -0.063*** | 0.017** | 0.044*** | -0.005 |
| | (0.006) | (0.008) | (0.011) | (0.007) | (0.011) | (0.007) |
| Member of a farmer | 0.027* | -0.003 | -0.082*** | 0.020 | -0.032 | 0.039* |
| cooperative | (0.015) | (0.019) | (0.026) | (0.020) | (0.031) | (0.020) |
| Credit facilities | 0.017 | -0.032* | 0.012 | -0.038** | -0.087*** | 0.083*** |
| | (0.018) | (0.018) | (0.026) | (0.019) | (0.031) | (0.019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Off-farm activities | -0.019 | 0.003 | 0.099*** | 0.033* | 0.065** | -0.037* |
| | (0.016) | (0.019) | (0.026) | (0.020) | (0.029) | (0.020) |
| Extension services | -0.050*** | 0.006 | -0.033 | -0.013 | 0.010 | 0.006 |
| | (0.015) | (0.017) | (0.023) | (0.019) | (0.027) | (0.018) |
| Climate information | -0.012 | 0.034* | 0.056** | 0.028 | -0.127*** | 0.015 |
| | (0.016) | (0.018) | (0.024) | (0.019) | (0.029) | (0.018) |
| Social safety nets | 0.037** | 0.009 | -0.159*** | -0.009 | 0.065** | 0.001 |
| | (0.015) | (0.019) | (0.024) | (0.020) | (0.026) | (0.017) |
| Agricultural diversification | -0.048*** | 0.019 | -0.048* | -0.000 | 0.008 | 0.017 |
| | (0.017) | (0.018) | (0.028) | (0.020) | (0.030) | (0.018) |
| Constant | -0.131*** | -0.149*** | 0.325*** | 0.003 | 0.029 | -0.194*** |
| | (0.040) | (0.044) | (0.067) | (0.060) | (0.070) | (0.047) |

Robust standard errors in parentheses; ME = Marginal effects
***p<0.01, **p<0.05, *p<0.1

### 4.4 MESR - Impacts of adoption combinations of CSAP on FNS outcomes

The impacts of the adoption of CSAP on rural farmers' food-nutrition outcomes (FNS – HDDS and HFIAS) were estimated using the predicted average treatment effect (ATT) derived from the MESR model. Table 4 presents the estimated impacts of different CSAP adoption categories (full, moderate, and single adoption) on HDDS and HFIAS for male-headed households (MHHs) and female-headed households (FHHs). The results compare observed (actual) outcomes for adopters with counterfactual outcomes had these households not adopted CSAP, thereby capturing both treatment effects and heterogeneity effects between adopters and non-adopters. Appendix Table A5 reports the impacts of different combinatory CSAP adoption packages like soil and water conservation (S), improved seed varieties (V), and irrigation technology (I) on food nutrition security outcomes among MHHs and FHHs in South Africa. This allows for a more granular assessment of how specific combinations of CSAP influence HDDS and HFIAS, while explicitly accounting for gender-differentiated impacts.

Results in Table 4 show that full adoption of CSAP yields substantial improvements in dietary diversity for both gender groups. Among MHHs, HDDS increases from 7.31 under the counterfactual non-adoption scenario to 10.12 with adoption, implying a treatment effect of 2.81 food groups. Similarly, FHHs experience an HDDS improvement of 2.88, rising from 6.16 (non-adoption) to 9.04 (adoption). These magnitudes are economically meaningful and consistent with the literature showing that multi-technology CSA adoption significantly enhances household nutrition through productivity and income channels. In terms of food security, full adoption significantly reduces food insecurity for both MHHs (−2.34) and FHHs (−2.26) on the HFIAS scale, indicating improved food access and stability. Positive heterogeneity effects for HDDS further suggest that households selecting into full adoption systematically achieve better nutritional outcomes than non-adopters.

For partial adoption, both MHHs and FHHs also experience significant gains, though the magnitude differs by gender. MHHs' HDDS increases from 6.07 to 9.18, corresponding to a treatment effect of 3.11, while FHHs record a smaller but still meaningful improvement of 2.15 (from 6.11 to 8.26). Partial adoption also substantially reduces food insecurity, with a stronger effect observed among MHHs (−4.06) than FHHs (−2.67). This pattern suggests that while partial adoption is beneficial for both groups, MHHs are better positioned to translate selective CSAP uptake into improved food security, likely due to complementary resources such as off-farm income and asset ownership. In contrast, single adoption of CSAP yields more modest nutritional gains. Among MHHs, HDDS increases marginally from 8.87 to 9.27, with a treatment effect of 0.40, whereas FHHs experience a relatively larger improvement of 1.68, from 8.21 to 9.89. Although single adoption reduces food insecurity for both MHHs (−4.36) and FHHs (−2.78), the effects are generally smaller than those observed under full or partial adoption. This suggests that isolated adoption of individual CSA practices may improve specific dimensions of food security but is less effective in delivering broad-based nutritional gains.

Notably, the results indicate that CSAP adoption significantly improves dietary diversity and reduces food insecurity, with stronger effects associated with higher levels and combinations of adoption. These findings are consistent with (Abegaz et al., 2023; Baiyegunhi et al., 2022), who posited that combined CSA practices outperform isolated adoption in enhancing farm productivity and household welfare. Similarly, (Abegaz et al., 2023; Omotoso & Omotayo, 2024a) emphasized that CSA adoption is a critical pathway for improving rural livelihoods under climate stress and land constraints. Evidence from Appendix Table A5 further reveals that male-headed households generally derive larger HDDS gains from most CSA adoption combinations, particularly those involving improved seeds and irrigation. While female-headed households also benefit from these combinations, the magnitude of improvements is comparatively smaller.

Consistent with (Atta-Aidoo et al., 2022; Mutengwa et al., 2023), these gender-differentiated impacts likely reflect persistent constraints faced by FHHs, including limited access to credit, extension services, and climate information, as well as smaller average farm sizes that restrict the scaling of CSA technologies. To ascertain the reliability and robustness of the findings, the impacts are estimated using nearest neighbour matching (NNM) techniques. Consequently, Appendix A6 illustrates the results of the robustness test, which buttressed that the combination adoption of CSAP leads to significant enhancements in the HDDS and HFIAS of smallholder rural farm households in South Africa.

**Table 4.** Average Treatment and Heterogeneity Effects estimation for actual and counterfactual – Household Dietary Diversity Score and Household Food Insecurity Access Score

| Outcomes | | | Adoption-decision estimations | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Male-headed households | | | Female-headed households | | |
| | | | **To adopt** | **Not to adopt** | **Treatment effects** | **To adopt** | **Not to adopt** | **Treatment effects** |
| | Full adoption | Adopters | 10.12 (4.17) | 7.31 (4.09) | 2.81*** (1.16) | 9.04 (5.05) | 6.16 (1.98) | 2.88*** (1.76) |
| | | Non-adopters | 8.03 (6.02) | 6.11 (3.05) | 1.92*** (0.98) | 7.25 (2.59) | 5.44 (1.99) | 1.81* (1.21) |
| | | Heterogeneity effects | 2.09 (1.02) | 1.20 (0.99) | 0.89 (1.01) | 1.79 (1.15) | 0.72 (0.25) | 1.07 (0.79) |
| **HDDS** | Moderate adoption | Adopters | 9.18 (4.77) | 6.07 (2.95) | 3.11 (1.78) | 8.26 (4.77) | 6.11 (3.09) | 2.15** (1.19) |
| | | Non-adopters | 6.20 (2.78) | 5.51 (1.45) | 0.69 (1.02) | 6.27 (2.70) | 5.15 (3.01) | 1.12* (0.69) |
| | | Heterogeneity effects | 2.98 (1.11) | 0.56 (0.36) | 2.42*** (1.04) | 1.99 (0.85) | 0.96 (0.66) | 1.03 (0.97) |
| | Single adoption | Adopters | 9.27 (5.71) | 8.87 (3.42) | 0.40*** (0.12) | 9.89 (5.42) | 8.21 (3.71) | 1.68 (1.13) |
| | | Non-adopters | 7.43 (2.95) | 6.19 (2.04) | 1.24 (0.97) | 7.55 (4.05) | 5.33 (1.93) | 2.22*** (0.99) |
| | | Heterogeneity effects | 1.84 (0.96) | 2.68 (1.07) | -0.84*** (0.24) | 2.34 (1.03) | 2.88 (1.12) | -0.54** (0.28) |
| | Full adoption | Adopters | 7.38 (5.02) | 9.72 (4.37) | -2.34** (1.18) | 8.12 (3.85) | 10.38 (6.78) | -2.26** (1.07) |
| | | Non-adopters | 11.95 (3.93) | 13.06 (5.71) | -1.11 (0.92) | 10.45 (4.82) | 14.22 (8.15) | -3.77*** (1.14) |
| | | Heterogeneity effects | -4.57 (1.77) | -3.34 (1.26) | -1.23 (0.98) | -2.33 (1.02) | -3.84 (1.82) | 1.51** (0.62) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **HFIAS** | Partial adoption | Adopters | 9.75 (5.95) | 13.81 (7.64) | -4.06*** (1.17) | 11.09 (8.02) | 13.76 (6.74) | -2.67*** (1.10) |
| | | Non-adopters | 12.92 (5.09) | 15.04 (7.15) | -2.12** (1.05) | 13.55 (7.92) | 14.21 (8.26) | -0.66*** (0.21) |
| | | Heterogeneity effects | -3.17 (1.20) | -1.23 (1.01) | -1.94** (0.95) | -2.46 (1.02) | -0.45 (0.17) | -2.01*** (0.56) |
| | Single adoption | Adopters | 10.11 (3.92) | 14.47 (7.12) | -4.36*** (1.06) | 9.26 (4.76) | 12.04 (7.11) | -2.78*** (1.08) |
| | | Non-adopters | 13.77 (8.11) | 15.06 (7.09) | -1.29 (0.99) | 11.77 (6.88) | 14.83 (10.84) | -3.06** (1.25) |
| | | Heterogeneity effects | -3.66 (1.21) | -0.59 (0.52) | -3.07* (1.78) | -2.51 (1.75) | -2.79 (2.02) | 0.28** (0.12) |

Note: ***, ** and * denote significant at 1%, 5% and 10%; Standard errors are in parentheses

## 5 Conclusion and policy implications

A substantial proportion of rural households in South Africa remain dependent on rainfed smallholder agriculture, making them highly vulnerable to climate variability and shocks. Declining agricultural productivity driven by climate change continues to undermine food and nutrition security (FNS) in these communities. This study employed a Multinomial Endogenous Switching Regression (MESR) framework to rigorously estimate the impacts of CSAP adoption on gender-differentiated FNS outcomes proxied by HDDS and HFIAS while correcting for selection bias arising from both observed and unobserved factors. The empirical results demonstrate that adoption decisions across different CSAP packages are significantly influenced by farm size, educational attainment, off-farm income, access to extension services, and climate information for both male-headed households (MHHs) and female-headed households (FHHs). However, the analysis reveals clear gender-specific constraints that shape both adoption pathways and welfare outcomes.

Notably, FHHs face systematic disadvantages in access to land, climate information, extension support, and effective credit utilization, which limit their ability to adopt individual CSAP technologies and to scale up beyond partial or single adoption. The average treatment effect estimates show that CSAP adoption significantly improves dietary diversity and reduces food insecurity for both gender groups, but with important differences in magnitude and structure. Notably, MHHs derive relatively larger gains from individual and partial CSAP adoption, reflecting their greater access to complementary assets such as land, off-farm income, and cooperative networks. Conversely, FHHs experience stronger welfare gains primarily when adopting integrated CSAP packages that combine soil and water conservation, improved seed varieties, and irrigation technologies. This finding suggests that integrated adoption compensates for women's resource constraints by generating synergistic productivity and income effects that are less dependent on scale and asset ownership.

Notably, these results have several direct policy implications. First, policies that promote CSAP adoption should move beyond uniform technology dissemination and instead target the specific constraints identified in the empirical analysis. For FHHs, improving access to tailored financial instruments such as low-collateral credit, group-based lending, or climate-risk-indexed grants is critical, given the observed negative or limited role of conventional credit in facilitating full adoption. Financial support should be explicitly linked to integrated CSAP packages, which the results show generate the largest food and nutrition gains for women. Second, the strong role of education and climate information in shaping adoption and outcomes underscores the need to strengthen gender-responsive extension systems. Extension services should prioritize female farmers' access to climate information, technical training, and advisory services that emphasize bundled CSAP adoption rather than isolated technologies. This could include women-focused extension programs, community-based climate information dissemination, and the use of radio and digital platforms to overcome mobility and time constraints faced by women.

Third, the findings highlight the importance of land and scale-related constraints. Given that farm size significantly enhances adoption and welfare outcomes among MHHs, policies aimed at improving women's land tenure security and access to productive land are essential for narrowing gender gaps in CSAP effectiveness. Where land expansion is not feasible, promoting labor-saving and scale-neutral CSA technologies can help FHHs achieve comparable welfare gains. Finally, social safety nets emerge as an important enabling factor for adoption, particularly for full CSAP uptake. Integrating CSAP promotion into existing social protection programs such as input subsidies or climate-responsive cash transfers would reduce risk exposure and encourage adoption among resource-constrained households, especially women. The study provides robust evidence that CSAP adoption improves food and nutrition security, but that its effectiveness is highly gender-differentiated and mediated by access to assets, information, and institutional support. Policies that explicitly address these empirically identified constraints rather than adopting a gender-neutral approach are more likely to enhance the resilience, productivity, and nutritional well-being of rural households in South Africa under climate change.

**Limitations of the study**

The study has several limitations. It relies on cross-sectional household data, which constrains the ability to make causal inferences and may be influenced by unobserved, time-invariant factors. Key variables, including food and nutrition indicators (HDDS, and HFIAS) and CSAP adoption, are self-reported, which may introduce recall or reporting bias. Mediating factors such as credit access, extension services, and cooperative membership may be jointly determined with adoption, potentially affecting estimates despite the use of MESR and NNM frameworks. The data also lack detailed information on intra-household labour allocation, decision-making, and time-use, limiting exploration of deeper gendered behavioral mechanisms. Finally, some instrumental variables used for robustness checks may be imperfect proxies, constraining the strength of causal interpretation. Despite these limitations, the study provides robust, gender-disaggregated evidence on the associations between CSAP adoption and household food and nutrition outcomes in South Africa.

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**Authors contributions** Conceptualization A.B.O., A.O.O; Methodology, Writing (original draft preparation) and Writing- Reviewing and Editing. The authors have read and approved the published version of the manuscript

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**Data availability** Data used in this research can be made available on tangible requests from the first author.

**Ethical approval** The Ethics Committee of North-West University's Faculty of Natural and Agricultural Sciences in South Africa authorized the ethical clearance (NWU-01267-23-A9) for the study. Prior to the distribution of questionnaires in the research areas, the Department of Rural, Environment and Agricultural Development, NW, South Africa, granted the researchers authorization to visit the study area. The researchers and participants in this study took great care to uphold the principles of privacy, autonomy, dignity, and respect.

**Informed Consent Statement** Informed consent was obtained from all the participants involved in the study. The consent of the participants was sought before the commencement of the study, and they were well-informed about their rights, including their right to withdraw from the study.

## References

Abegaz, A., Abera, W., Jaquet, S., & Tamene, L. D. (2023). A meta-analysis of adoption studies of climate-smart agriculture practices (CSAPs) in Ethiopia. *Climate Risk Management*.

Ahmed, M., Asim, M., Ahmad, S., & Aslam, M. (2023). Climate change, agricultural productivity, and food security. In *Global agricultural production: Resilience to climate change* (pp. 31-72). Springer.

Akano, O., Modirwa, S., Oluwasemire, K., & Oladele, O. (2023). Awareness and perception of climate change by smallholder farmers in two agroecological zones of Oyo state Southwest Nigeria. *GeoJournal*, *88*(1), 39-68.

Akpan, A. I., & Zikos, D. (2023). Rural Agriculture and Poverty Trap: Can Climate-Smart Innovations Provide Breakeven Solutions to Smallholder Farmers? [Article]. *Environments - MDPI*, *10*(4), Article 57. https://doi.org/10.3390/environments10040057

Antwi-Agyei, P., Wiafe, E. A., Amanor, K., Baffour-Ata, F., & Codjoe, S. N. A. (2021). Determinants of choice of climate change adaptation practices by smallholder pineapple farmers in the semi-deciduous forest zone of Ghana. *Environmental and Sustainability indicators*, *12*, 100140.

Atta-Aidoo, J., Antwi-Agyei, P., Dougill, A. J., Ogbanje, C. E., Akoto-Danso, E. K., & Eze, S. (2022). Adoption of climate-smart agricultural practices by smallholder farmers in rural Ghana: An application of the theory of planned behavior. *PLoS Climate*, *1*(10), e0000082.

Ayodele, M. A., Omotoso, A. B., Sulaimon, I. O., & Daud, S. A. (2025). Vulnerability Assessment of Food Crop Production and Climate Change: Implication for Agricultural Productivity and Development in Nigeria. *Rural and Regional Development*, *3*(3), 10008.

Baiyegunhi, L. J. S., Akinbosoye, F., & Bello, L. O. (2022). Welfare impact of improved maize varieties adoption and crop diversification practices among smallholder maize farmers in Ogun State, Nigeria [Article]. *Heliyon*, *8*(5), Article e09338. https://doi.org/10.1016/j.heliyon.2022.e09338

Batisani, N., Pule-Meulenberg, F., Batlang, U., Matteoli, F., & Tselaesele, N. (2021). Retooling Smallholder Farming Systems for Climate Change Resilience Across Botswana Arid Zones. In *African Handbook of Climate Change Adaptation: With 610 Figures and 361 Tables* (pp. 339-362). https://doi.org/10.1007/978-3-030-45106-6_168

Brenya, R., Jiang, Y., Sampene, A. K., & Zhu, J. (2024). Food security in sub-Sahara Africa: Exploring the nexus between nutrition, innovation, circular economy, and climate change. *Journal of Cleaner Production*, *438*, 140805.

Danso-Abbeam, G., Ehiakpor, D. S., & Aidoo, R. (2018). Agricultural extension and its effects on farm productivity and income: insight from Northern Ghana. *Agriculture & Food Security*, *7*(1), 1-10.

Davis-Reddy, C. (2018). *Assessing vegetation dynamics in response to climate variability and change across sub-Saharan Africa* Stellenbosch: Stellenbosch University]. Nature.

Dechezleprêtre, A., Fabre, A., Kruse, T., Planterose, B., Chico, A. S., & Stantcheva, S. (2022). *Fighting climate change: International attitudes toward climate policies*.

FAO. (2021). Aligning agriculture and climate policy. *Nature climate change*, *7*(5), 307-309.

Fusco, G., Melgiovanni, M., Porrini, D., & Ricciardo, T. M. (2020). How to improve the diffusion of climate-smart agriculture: What the literature tells us [Review]. *Sustainability (Switzerland)*, *12*(12), Article 5168. https://doi.org/10.3390/su12125168

Gwara, S., Wale, E., & Odindo, A. (2022). Behavioral intentions of rural farmers to recycle human excreta in agriculture. *Scientific reports*, *12*(1), 5890.

Harper, A., Rothberg, A., Chirwa, E., Sambu, W., & Mall, S. (2023). Household Food Insecurity and Demographic Factors, Low Birth Weight and Stunting in Early Childhood: Findings from a Longitudinal Study in South Africa. *Maternal and Child Health Journal*, *27*(1), 59-69.

Issahaku, G., & Abdulai, A. (2020). Can farm households improve food and nutrition security through adoption of climate-smart practices? empirical evidence from Northern Ghana. *Applied Economic Perspectives and Policy*, *42*(3), 559-579.

Kangogo, D., Dentoni, D., & Bijman, J. (2021). Adoption of climate-smart agriculture among smallholder farmers: Does farmer entrepreneurship matter? [Article]. *Land Use Policy*, *109*, Article 105666. https://doi.org/10.1016/j.landusepol.2021.105666

Lal, R. (2020). Integrating animal husbandry with crops and trees. *Frontiers in Sustainable Food Systems*, *4*, 113.

Maindi, N. C., Osuga, I. M., & Gicheha, M. G. (2020). Advancing climate smart agriculture: Adoption potential of multiple on-farm dairy production strategies among farmers in Murang'a County, Kenya [Article]. *Livestock Research for Rural Development*, *32*(4). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85084680289&partnerID=40&md5=9a3fb4530bb06905c5e45c0ab7f35c25

Merga, G., Sileshi, M., & Zeleke, F. (2023). Welfare impact of improved maize varieties adoption among smallholder farmers in Amuru district of Horo Guduru Wollega, Ethiopia. *Cogent Economics & Finance*, *11*(1), 2207923.

Mirzabaev, A., Olsson, L., Kerr, R. B., Pradhan, P., Ferre, M. G. R., & Lotze-Campen, H. (2023). Climate change and food systems. *Science and Innovations for Food Systems Transformation*, 511.

Mishra, A., Ketelaar, J. W., Uphoff, N., & Whitten, M. (2021). Food security and climate-smart agriculture in the lower Mekong basin of Southeast Asia: Evaluating impacts of system of rice intensification with special reference to rainfed agriculture. *International Journal of Agricultural Sustainability*, *19*(2), 152-174.

Mutea, E., Rist, S., & Jacobi, J. (2020). Applying the theory of access to food security among smallholder family farmers around North-West Mount Kenya. *Sustainability*, *12*(5), 1751.

Mutengwa, C. S., Mnkeni, P., & Kondwakwenda, A. (2023). Climate-Smart Agriculture and Food Security in Southern Africa: A Review of the Vulnerability of Smallholder Agriculture and Food Security to Climate Change. *Sustainability*, *15*(4), 2882.

Omotayo, A. O., Olagunju, K. O., Omotoso, A. B., Ogunniyi, A. I., Otekunrin, O. A., & Daud, A. S. (2021). Clean water, sanitation and under-five children diarrhea incidence: Empirical evidence from the South Africa's General Household Survey. *Environmental Science and Pollution Research*, *28*, 63150-63162.

Omotayo, A. O., & Omotoso, A. B. (2025). Climate-smart agricultural technology and gender-differentiated food, and water security: Evidence from smallholder sunflower (Helianthus annuus L.) Farmers. *Agricultural Water Management*, *308*, 109276.

Omotayo, A. O., Omotoso, A. B., Daud, S. A., Omotayo, O. P., & Adeniyi, B. A. (2022). Rising food prices and farming households food insecurity during the COVID-19 pandemic: policy implications from SouthWest Nigeria. *Agriculture*, *12*(3), 363.

Omotoso, A. B. (2026). Bridging the healthcare-agriculture nexus: pathways to enhancing agricultural productivity and rural development in Nigeria. *Frontiers in Sustainable Food Systems*, *10*, 1930441.

Omotoso, A. B., Letsoalo, S. S., Daud, S. A., Tshwene, C., & Omotayo, A. O. (2024). Climate-smart agricultural practices, productivity, and food-nutrition security in rural South Africa: A dataset of smallholder maize farmers. *Data in Brief*, *55*, 110725.

Omotoso, A. B., & Omotayo, A. O. (2024a). Enhancing dietary diversity and food security through the adoption of climate-smart agricultural practices in Nigeria: a micro level evidence. *Environment, Development and Sustainability*, 1-18.

Omotoso, A. B., & Omotayo, A. O. (2024b). Impact of behavioural intention to adopt climate-smart agricultural practices on the food and nutrition security of farming households: A microeconomic level evidence. *Climatic Change*, *177*(7), 117.

Omotoso, A. B., & Omotayo, A. O. (2024c). The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa. *Regional Environmental Change*, *24*(1), 1.

Omotoso, A. B., & Omotayo, A. O. (2026). Impacts of climate change adaptation mechanisms on smallholder maize (Zea mays L.) farmers' productivity. *Sustainable Futures*, *11*, 101613.

Outhwaite, C. L., McCann, P., & Newbold, T. (2022). Agriculture and climate change are reshaping insect biodiversity worldwide. *Nature*, *605*(7908), 97-102.

Robinson, S. a. (2020). Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(4), e653.

Rosenstock, T. S., Lamanna, C., Namoi, N., Arslan, A., & Richards, M. (2019). What is the evidence base for climate-smart agriculture in East and Southern Africa? A systematic map. *The climate-smart agriculture papers: Investigating the business of a productive, resilient and low emission future*, 141-151.

Segbefia, E., Dai, B., Adotey, P., & Sampene, A. K. (2023). A step towards food security: The effect of carbon emission and the moderating influence of human capital. Evidence from Anglophone countries. *Heliyon*, *9*(12).

Sikka, A. K., Islam, A., & Rao, K. (2018). Climate-smart land and water management for sustainable agriculture. *Irrigation and Drainage*, *67*(1), 72-81.

Su, F., Liu, Y., Chen, S.-J., & Fahad, S. (2023). Towards the impact of economic policy uncertainty on food security: Introducing a comprehensive heterogeneous framework for assessment. *Journal of Cleaner Production*, *386*, 135792.

Suyani, N. K., Singh, M. K., & Brahmchari, R. K. (2023). Climate Change and Coral Reef Ecosystem: Impacts and Management Strategies. In *Outlook of Climate Change and Fish Nutrition* (pp. 63-74). https://doi.org/10.1007/978-981-19-5500-6_6

Tekeste, K. (2021). Climate-Smart Agricultural (CSA) practices and its implications to food security in Siyadebrina Wayu District, Ethiopia. *African Journal of Agricultural Research*, *17*(1), 92-103.

Tilahun, G., Bantider, A., & Yayeh, D. (2023). Analyzing the Impact of Climate-Smart Agriculture on Household Welfare in Subsistence Mixed Farming System: Evidence from Geshy Watershed, Southwest Ethiopia. *Global Social Welfare*, 1-13.

UNICEF. (2023). The state of food security and nutrition in the world 2023.

Wassmann, R., Villanueva, J., Khounthavong, M., Okumu, B. O., Vo, T. B. T., & Sander, B. O. (2019). Adaptation, mitigation and food security: Multi-criteria ranking system for climate-smart agriculture technologies illustrated for rainfed rice in Laos. *Global Food Security*, *23*, 33-40.

WFP, W. (2021). Asia and the Pacific–Regional Overview of Food Security and Nutrition 2022.

## Appendix A

**Table A1.** Test of validity of the selection instrument

| **Variable** | **Coef.** | **Robust SE** |
|---|---|---|
| Age | -0.001 | 0.028 |
| Gender | 0.193 | 0.160 |
| Household size | 0.438*** | 0.054 |
| Marital status | 0.781 | 0.523 |
| Educational status o | 0.050 | 0.057 |
| Years of experience | 0.067** | 0.034 |
| Off-farm income | 0.147 | 0.489 |
| Extension service | 0.283*** | 0.093 |
| Land ownership | 0.065 | 0.098 |
| Total farm size used in cultivating | 0.083*** | 0.006 |
| Total land used for sunflower cultivation | 0.122 | 0.390 |
| Agricultural diversification | 0.630** | 0.344 |
| Source of finance | 0.192 | 0.178 |
| Membership of cooperative society | 0.157*** | 0.033 |
| Access to credit | 0.355*** | 0.088 |
| Information on climate change | 0.199*** | 0.028 |
| Social safety net | 0.0391 | 0.170 |
| Constant | 0.164*** | 0.022 |

Note: *** p<0.01, ** p<0.05, * p<0.1
Non-adopter is the reference category

**Table A2.** HDDS – Second stage estimates of the MESR

| **Variables** | **Male-headed** | | **Female-headed** | |
|---|---|---|---|---|
| | Coef. | SE | Coef. | SE |
| Age | 0.115*** | 0.0311 | 0.003 | 0.011 |
| Household size | -0.116 | 0.283 | -0.824*** | 0.315 |
| Marital status | 0.198*** | 0.053 | 0.310 | 0.790 |
| Educational status | 0.286 | 0.789 | 0.152* | 0.080 |
| Years of experience | 0.115*** | 0.031 | 0.187 | 0.108 |
| Land ownership | -0.116 | 0.155 | 0.036** | 0.018 |
| Total farm size used in cultivating | -0.761** | 0.312 | 0.368 | 0.472 |
| Agricultural diversification | 0.138 | 0.237 | 0.063 | 0.054 |
| Source of financing farm operation | 0.014 | 0.246 | 0.107** | 0.040 |
| Access to credit | 0.5431** | 0.4678 | 0.147* | 0.081 |
| Social safety net | -0.242 | 0.260 | 0.075 | 0.085 |
| Sigma2 | 0.091*** | 0.009 | 0.821*** | 0.330 |
| Rho 1 | 0.062 | 0.147 | | |
| Rho 2 | | | -0.609 | 0.421 |
| Constant | 0.261*** | 0.044 | -0.056*** | 0.021 |

Note: ***, **, and * denotes significant at 1%, 5% and 10% respectively

**Table A3.** HFIAS – Second stage estimates of the MESR

| Variables | Male-headed | | Female-headed | |
|---|---|---|---|---|
| | **Coef.** | **SE** | **Coef.** | **SE** |
| Age | 0.315 | 0.386 | 0.124 | 0.602 |
| Household size | 0.541 | 0.353 | 0.035* | 0.018 |
| Marital status | 0.610 | 0.514 | 0.176 | 0.195 |
| Educational status | 0.019 | 0.073 | 0.005 | 0.018 |
| Years of experience | -0.344*** | 0.060 | 0.013 | 0.107 |
| Land ownership | -0.594*** | 0.085 | 0.033 | 0.041 |
| Total farm size used in cultivating | -0.399*** | 0.058 | -0.024*** | 0.007 |
| Agricultural diversification | 0.314*** | 0.046 | 0.0051 | 0.0384 |
| Source of financing | 0.471 | 0.387 | 0.377*** | 0.101 |
| Access to credit | -0.183* | 0.097 | 0.078*** | 0.005 |
| Social safety net | -0.049* | 0.026 | 0.189 | 0.210 |
| Sigma2 | 0.471 | 0.389 | 0.612 | 0.402 |
| Rho1 | 0.282* | 0.108 | | |
| Rho2 | | | 0.103 | 0.112 |
| Constant | 0.271*** | 0.098 | 0.109*** | 0.047 |

Note: ***, **, and * denotes significant at 1%, 5% and 10% respectively

**Table A4.** Typologies of CSA practices adopted by smallholder farmers in South Africa

| **Choice (*j*)** | **CSAT** | **Soil and water conservation (S)** | | **Improved Seed Varieties (V)** | | **Irrigation Technology (I)** | | **Frequency** | **Percentage (%)** |
|---|---|---|---|---|---|---|---|---|---|
| | | $S_1$ | $S_0$ | $V_1$ | $V_0$ | $I_1$ | $I_0$ | | |
| **1** | $S_0V_0I_0$ | | | | | | | 213 | 18.05 |
| **2** | $S_1V_0I_0$ | ♣ | | | | | | 81 | 6.86 |
| **3** | $S_0V_1I_0$ | | | ♣ | | | | 96 | 8.14 |
| **4** | $S_0V_0I_1$ | | | | | ♣ | | 236 | 20.00 |
| **5** | $S_1V_1I_0$ | ♣ | | ♣ | | | | 103 | 8.73 |
| **6** | $S_1V_0I_1$ | ♣ | | | | ♣ | | 270 | 22.88 |
| **7** | $S_0V_1I_1$ | | | ♣ | | ♣ | | 104 | 8.81 |
| **8** | $S_1V_1I_1$ | ♣ | | ♣ | | ♣ | | 77 | 6.53 |
| **Total** | | | | | | | | 1180 | 100 |

**Table A5.** ATT Estimates of MESR model – Household Dietary Diversity Score and Household Food Insecurity Access Score

| | Treated group | Control group | Gender-differentiated households | | |
|---|---|---|---|---|---|
| | | | **Pooled** | **Male** | **Female** |
| | $S_1V_0I_0$ | $S_0V_0I_0$ | 0.043 (0.032) | 0.184***(0.043) | 0.107** (0.068) |
| | $S_0V_1I_0$ | $S_0V_0I_0$ | 1.487***(0.039) | 1.586***(0.053) | 1.389***(0.052) |
| | $S_0V_0I_1$ | $S_0V_0I_0$ | 0.444***(0.028) | 0.731***(0.034) | 0.121***(0.042) |
| **HDDS** | $S_1V_1I_0$ | $S_0V_0I_0$ | 0.161***(0.062) | 0.594***(0.085) | 0.344***(0.074) |
| | $S_1V_0I_1$ | $S_0V_0I_0$ | 0.371***(0.042) | 0.399***(0.058) | 0.344***(0.060) |
| | $S_0V_1I_1$ | $S_0V_0I_0$ | 0.034(0.138) | 0.042(0.211) | 0.024(0.167) |
| | $S_1V_1I_1$ | $S_0V_0I_0$ | 0.110(0.189) | 0.670***(0.234) | 0.561***(0.283) |
| | $S_1V_0I_0$ | $S_0V_0I_0$ | -2.491***(0.023) | -2.362***(0.033) | --2.623***(0.029) |
| | $S_0V_1I_0$ | $S_0V_0I_0$ | -2.492***(0.022) | -2.363***(0.033) | ---2.624***(0.028)) |
| | $S_0V_0I_1$ | $S_0V_0I_0$ | -3.274***(0.005) | -3.278***(0.004) | -3.268***(0.005) |
| **HFIAS** | $S_1V_1I_0$ | $S_0V_0I_0$ | -5.619***(0.076) | -5.369***(0.105) | -5.909***(0.098) |
| | $S_1V_0I_1$ | $S_0V_0I_0$ | -2.356***(0.003) | -2.357***(0.004) | -2.353***(0.003) |
| | $S_0V_1I_1$ | $S_0V_0I_0$ | -2.299***(0.051) | -2.020***(0.063) | -2.626***(0.0668) |
| | $S_1V_1I_1$ | $S_0V_0I_0$ | -0.524***(0.104) | -0.783***(0.149) | -0.213(0.129) |

Robust standard errors are in parenthesis. ***$p < 0.01$ and *$p < 0.1$

**Table A6.** Robustness test using NNM

| | Treated group | Gender-differentiated households | |
|---|---|---|---|
| | | **Male** | **Female** |
| | Full adoption | 0.365*** (0.101) | 0.561*** (0.129) |
| **HDDS** | Moderate adoption | -0.387 (0.853) | 0.154 (0.164) |
| | Single adoption | 0.056*** (0.022) | -0.186 (0.264) |
| | Full adoption | -0.034 (0.138) | -1.586***(0.053) |
| **HFIAS** | Partial adoption | 0.110 (0.189) | -0.731***(0.034) |
| | Single adoption | -0.783***(0.149) | 0.184***(0.043) |

Robust standard errors are in parenthesis. ***$p < 0.01$ and **$p < 0.05$

**Appendix Table B1. Variable descriptions**

| Selected interest Variables | Variable description | Coding/Measurement |
|---|---|---|
| Age | Actual age of the household head (HH) at the time of survey | Years (continuous) |
| Income | Total income earned from the sale of farm produce during 2023/2024 season | Rands (continuous) |
| Off-farm activities | Participation of the household head in off-farm income-generating activities such as trading, food processing and marketing of agricultural produces | Dummy: 1 = Yes, 0 = No |
| Household size | Total number of individuals living in the household | Count (continuous) |
| Farm size | Total land area cultivated by the household | Hectares (continuous) |
| Education status | Whether the household head has any formal education | Dummy: 1 = Educated, 0 = Not educated |
| Climate information | Access to climate or weather-related information (such as weather forecasts, and advisories) | Dummy: 1 = Yes, 0 = No |
| Extension service | Access to agricultural extension services | Dummy: 1 = Yes, 0 = No |
| Credit facilities | Access to credit for agricultural or household activities | Dummy: 1 = Yes, 0 = No |
| Member of cooperative | Membership of the household head in an agricultural or social cooperative | Dummy: 1 = Member, 0 = Non-member |
| Agricultural diversification | Engagement in more than one crop and/or livestock enterprise | Dummy: 1 = Diversified, 0 = Not diversified |
| Information from radio | Use of radio as a source of agricultural or climate-related information | Dummy: 1 = Yes, 0 = No |
| Community meetings | Participation in community meetings related to agriculture or development activities | Dummy: 1 = Yes, 0 = No |
| Social safety net | Access to government social protection programs (such as cash transfers, and input subsidies) | Dummy: 1 = Access, 0 = No access |

## Mission

To strengthen local capacity for conducting independent, rigorous inquiry into the problems facing the management of economies in sub-Saharan Africa.

The mission rests on two basic premises: that development is more likely to occur where there is sustained sound management of the economy, and that such management is more likely to happen where there is an active, well-informed group of locally based professional economists to conduct policy-relevant research.

Bringing Rigour and Evidence to Economic Policy Making in Africa

- Improve quality.
- Ensure Sustainability.
- Expand influence.

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