



Impact of behavioural intention to adopt climate-smart agricultural practices on the food and nutrition security of farming households: A microeconomic level evidence

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Abstract

The study examined the behavioural intention to adopt climate-smart agricultural practices (CSA) and its impact on the food-nutrition security (FNS) of farming households in South Africa. We employed a multistage sampling procedure to select rural maize farmers across the selected villages. To determine the impacts of behavioural adoption of CSA on the FNS of farming households, endogenous switching regression model (ESRM) was employed, while household dietary diversity score (HDDS) and household food insecurity access score (HFIAS) were used to determine the FNS status of the households. The findings emphasized the significance of the behavioural intentions of rural maize farmers, assessed through their attitudinal dimensions (measured in terms of perceived social norms, behavioural intentions, and control) in influencing the adoption decision of CSA practices, hence CSA adoption positively impacts FNS in South Africa. The result indicates that households that adopt CSA observe a 27% and 23% increase in HDDS and a decrease in HFIAS compared to those who do not adopt CSA practices, respectively. Thus, the outcome illustrates that the adoption of CSA practices substantially enhances the HDDS and HFIAS of rural maize farming households in South Africa. Following this backdrop, a concerted effort to raise knowledge of CSA practices through disseminating pertinent information will exert influence on the farmers' adoption behaviour towards CSA practices, which is capable of improving the FNS of rural maize farmers.

Keywords Behavioural factors · Climate variation · Dietary Diversity · Food policy · Sustainability

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1 Introduction

In sub-Saharan Africa (SSA), the adoption of agricultural technology follows a trajectory outlined by the Theory of Technology Adoption, which denotes how farmers are likely to adopt enhanced agricultural technology and how this adoption influences food security, with early innovators paving the way for broader acceptance among farmers (Kahneman and Tversky 2013). Subsequently, behavioural economics principles highlight the importance of addressing cognitive biases and social influences in farmers' decision-making processes regarding improved agricultural technology adoption, such as climate-smart agricultural practices (CSA) (Thaler 2016). Strategies to promote technology adoption and enhance food security include providing clear information about CSA benefits, leveraging social norms, and peer networks, and offering incentives to overcome present bottlenecks (Thaler 2016; Wassmann et al. 2019). By integrating insights from both theories, policymakers can design targeted interventions that encourage widespread adoption of CSA practices, ultimately improving agricultural sector resilience and food security in SSA.

The agricultural sector is currently experiencing a notable decrease in productivity as a result of the impacts of global climate change, which severely affects productivity and food-nutrition-development in sub-Saharan Africa (SSA) (Kangogo et al. 2021; Maindi et al. 2020). Additionally, (FAO 2021; Omotoso and Omotayo 2024b) regional assessment cautions that a temperature increase of more than 2 degrees Celsius would result in reduced yields for staple crops throughout much of SSA (for example, 20% - 40% lower maize yields in Southern Africa), leading to poor food-nutrition security (FNS) of the households (Akanbi et al. 2021; Omotoso et al. 2023; Tione et al. 2022). Notably, grain yields in South Africa, especially maize, which is the major staple food of the households, have declined by 25% (Akanbi et al. 2021; Akano et al. 2023; Bahri et al. 2021). Thus, this situation had severe impacts on the livelihoods and FNS of rural farmers, who contribute around 65% of the country's food system (Akanbi et al. 2021).

More so, the impact of climate change on FNS is increasingly severe (Ali 2021; Issahaku and Abdulai 2020) while the impact is compounded by the country's socio-economic, and environmental trends coupled with population growth, limited land and water resources, economic transformation, and challenges in agriculture and the food systems value chain (FAO 2021; Omotoso and Omotayo 2024a). These trends have prompted food security experts to conclude that agriculture and FNS in South Africa will face significant challenges in a world where temperatures are continually rising (Akano et al. 2023; Issahaku and Abdulai 2020; Tione et al. 2022). This prognosis prompted the Food and Agriculture Organization (FAO) as well as other international multilateral organizations to contend that the implementation of climate-smart agriculture (CSA) practices are crucial for the country to enhance FNS (Akpan and Zikos 2023; Omotayo et al. 2022; Ricart et al. 2022).

In South Africa, where maize farming is a vital component of the economy and livelihoods of rural dwellers, the increasing challenges posed by climate change threaten its production and the food-nutrition security (FNS) of farming households (Omotoso et al. 2023). It is anticipated that maize yields from rain-fed agriculture will decrease by as much as 50% by 2030, significantly impacting access to food for rural households (Daud et al. 2018; Worku et al. 2020). In light of these pessimistic projections, it is unsurprising that the implementation of CSA practices is crucial for sustaining food crop yields (Ali 2021; Atta-Aidoo et al. 2022).

Consequently, there is increasing literature on CSA adoption and implementation on agricultural production in South Africa (Akanbi et al. 2021; Davis-Reddy 2018; Omotayo et al. 2021; Shen et al. 2021). However, several elements beyond socio-demographic considerations and economic incentives impact the adoption of agricultural practices (Ali 2019; Atta-Aidoo et al. 2022). Individual and intrinsic motives, also known as behavioural intentions, have a significant role in shaping these adoption decisions (Di Falco et al. 2011; Gwara et al. 2022). Research gaps exist regarding comprehensive empirical studies that quantitatively assess the direct impact of the attitudinal dimension of farmers on the adoption-decision impacts of CSA on the FNS outcomes of farming households in South Africa. Existing research tends to focus more on adoption rates and qualitative assessments of CSA, leaving a need for rigorous studies that measure changes in dietary diversity, and nutritional outcomes resulting from behavioural adoption of CSA at the household level in the South African context.

Therefore, identified strategies aimed at promoting CSA adoption did not effectively target the underlying behavioural determinants, resulting in suboptimal outcomes. Likewise, there is a lack of integration of behavioural insights into agricultural policies and programs aimed at promoting CSA adoption. As a result, the relationship between farmers' behavioural intentions, CSA adoption, and food-nutrition security outcomes needs further exploration. Understanding how behavioural factors influence food security and nutrition outcomes can inform more holistic approaches to agricultural development in South Africa.

Consequently, this research aims to make a scholarly contribution to the existing body of literature on climate change, and its impact on agriculture through the provision of a micro-level analysis of the interplay between CSA and FNS. Specifically, this study examines the impact of behavioural intentions of farm households' decision to adopt CSA, in response to long-term changes in key climatic factors like temperature and rainfall on households' FNS. This research appears to be pertinent given that the predominant discourse around climate change in the agricultural sector has been focused on the consequences of climate change, rather than on the need for adaptation strategies and the behavioural intention in CSA adoption-decisions. Despite the potential benefits of adopting CSA practices, there is a critical gap in understanding the behavioral intentions of farmers to adopt CSA and how this adoption impacts FNS. This gap hinders the development of effective strategies and policies aimed at promoting sustainable agriculture and enhancing the nutritional well-being of farming communities.

Conversely, micro-evidence impact of rainfall, temperature, and climate related adaptation strategies on food production and FNS is very scanty. It has become apparent to gain insight into people's actions across contexts because it offers a socio-psychological foundation for understanding human behaviour in a variety of domains, as well as a platform for encouraging behaviour change towards adopting sustainable agricultural practices that would improve households' FNS (Omotoso and Omotayo 2024a). The study will add to the research on the synergy between households' FNS and CSA adoption by determining the relative importance of farmers' behavioural intentions towards CSA practices in the maize farming system. The insights would inform policymakers about potential household actions that might favourably affect farmers' behaviour intention towards the adoption of CSA practices and their impact on the FNS of rural farming households in South Africa.

2 Behavioral Intention, Climate-Smart Agriculture and Food-Nutrition Security

Farmers in highly susceptible SSA agro-climatic zones, are constantly deploying and reorienting agricultural systems to promote FNS in response to climate change's new realities (Bahri et al. 2021; Paul et al. 2018). Climate-smart agriculture endeavours to enhance the adaptability of agricultural systems and livelihoods, while concurrently mitigating the vulnerability to FNS in both current and future contexts (FAO 2013; Lipper et al. 2014). In South Africa, CSA practices such as conservation tillage (minimal or zero-tillage), the adoption of enhanced and drought-tolerant cultivars, crop rotation, mixed-cropping, and crop diversification allow farmers to produce food sustainably, thus enhancing their food-nutrition security (Bahri et al. 2021; Paul et al. 2018). However, the overall transformation of the FNS is still not well established due to the behaviour intentions of farmers towards CSA adoptions (Ali 2019; Omotoso et al. 2022).

Behavioral intentions, which denotes an individual's subjective intention and readiness to perform a specific behaviour plays a crucial role in driving the adoption of CSA practices to enhance their households' FNS (Atta-Aidoo et al. 2022; Kangogo et al. 2021). Farmers' attitudes, beliefs, and perceptions about climate-smart practices influence their decisions to implement them (Amadu et al. 2020; Outhwaite et al. 2022). Interestingly, if farmers have a positive attitude toward climate-smart practices, perceive them as beneficial for their farms, environment, and household welfare, and believe they have the necessary resources and support, their behavioural intention to adopt these practices is more likely to be positive and strong (Atta-Aidoo et al. 2022; Outhwaite et al. 2022; Ren et al. 2018).

Thus, promoting positive attitudes and increasing knowledge about climate-smart practices can influence farmers' behavioral intentions in favor of sustainable agricultural practices and transform them into a better FNS households (Adesete et al. 2022; Gwara et al. 2022). Additionally, the synergy between farmers' behavioral intentions, climate-smart agriculture, and FNS highlights the potential for positive impacts on both agricultural systems and human well-being (Aker et al. 2023; Jellason et al. 2021). Thus, fostering positive attitudes towards CSA adoption, promoting knowledge-sharing, and providing support for sustainable agricultural practices, would contribute to a more secure food supply, improved nutrition, and enhanced environmental sustainability. We anticipate that the findings from this study will guide policies and interventions tailored to the specific challenges faced by South African farmers.

2.1 Conceptual and Theoretical Framework: Theory of Planned Behaviour (TPB)

Following (Atta-Aidoo et al. 2022; Issahaku and Abdulai 2020), the theory of planned behaviour (TPB) was used in this study to comprehend the various ways that the adoption of CSA practices has impacted smallholder farmers' FNS. The TPB is predicated on the idea that people's judgments, choices, and actions are influenced by behavioural intentions when it comes to implementing certain technologies (Atta-Aidoo et al. 2022; Gwara et al. 2022). Thus, promoting a sustainable increase in agricultural productivity, preparing for the challenges posed by climate change, and reducing or eliminating greenhouse gas (GHG) emissions resulting from agricultural practices are the three objectives of CSA practices. In this framework (Appendix 1), the CSA was designed to combine these three

objectives to improve the FNS and agricultural output of smallholder maize farmers in the face of climate change.

The goal of the conceptual framework (TPB), as shown in Appendix 1, is to explain how adopting climate-smart agricultural (CSA) practices might help smallholder maize farmers reduce the negative effects of climate change on their production and FNS. The objectives of the CSA framework are to lower greenhouse gas emissions, encourage sustainable agriculture production, and foster a favourable perception of CSA initiatives (Atta-Aidoo et al. 2022). Identifying potential barriers to the adoption of new agricultural technology assists maize farmers in adapting to the problems posed by climate change. Adopting the TPB to assess farmers' intentions to implement sustainable farming techniques, facilitates the adoption of CSA practices by offering support, resources, and instruction for effective utilization.

3 Research methodology

3.1 Study area

We conducted the study in North-West province (Appendix 2), South Africa. The province accounted for about 9.0% of the total geographical area of South Africa, measuring 106,512 square kilometers and ranks as the fourth smallest province in the nation (Akanbi et al. 2021). Mining and farming, notably maize production, provide significant contributions to the province's economy (Akanbi et al. 2021; Akpan and Zikos 2023). Interestingly, the majority of South African rural farm households rely heavily on maize farming, which thrives in various locations across the nation due to its adaptability to diverse climatic conditions (Akanbi et al. 2021; Issahaku and Abdulai 2020). It is a staple food crop that accounts for about 70% of the country's total grain production and covers approximately 65% of cropping land area. Its cultivation is critical for ensuring FNS and supporting the livelihoods of many rural farming households through revenue generation and job creation (Aidoo et al. 2021; Ricart et al. 2022).

North-West province has constantly been placed (third) among the top provinces in South Africa for maize cultivation owing to its favourable agro-climatic conditions, including rich soils and human capital, which make it appropriate for maize production (Akanbi et al. 2021; Maindi et al. 2020). Climate change has negatively impacted the province's ecological balance and biodiversity due to consistent temperature increases and erratic precipitation (Aidoo et al. 2021; Ricart et al. 2022). Notably, maize production contributes substantially to the province's economy and the residents' means of subsistence (Aidoo et al. 2021; Ricart et al. 2022). Research on the behavioural intention of smallholder maize farmers in adopting CSA would shed light on the potential economic consequences of climate change, such as changes in yield, farm incomes and the FNS of farm households. This data can inform both local and national economic planning and decision-making.

3.2 Sampling procedures and data analysis

We gathered primary data for this study through a cross-sectional field survey of smallholder maize farmers in the North-West province following the 2022 agricultural season. The data collected is suitable and adequate for assessing food diversity arising from dietary quality and adequacy as a result of output from farms and CSA practices adopted to improve farming operations. We used a multistage selection technique to select 316

smallholder maize farmers from the province's four municipalities—Bojanala District, Ngaka Modiri Molema, Dr. Kenneth Kaunda, and Dr. Ruth Segomotsi Mompati District Municipality—who participated in extension training on improving agricultural technology. To guarantee statistical representativeness, the initial step included choosing all four municipalities in the province of North-West. The second step, with the assistance of the district extension staff, entailed selecting fifteen local communities that were well-known for producing maize in the North-West.

Local extension officials assisted in randomly selecting two villages from each local municipality, totaling 30 villages, known for their subsistence maize growing. At the end of the process, with the help of district extension officers, 316 smallholder maize farmers in the villages were selected from a list of all smallholder maize farmers. A descriptive statistic was used to describe the collected data, which included the socioeconomic status of the smallholder farmers, the types of food that households consume, the farm's output, and the different CSAs that the farmers adopted in the 2022 growing season. This led to the creation of frequencies, means, and standard deviations (SD). We employed the Endogenous Switching Regression Model (ESRM) to analyze the impact of CSA adoption on the food-nutrition security (FNS) of rural farmers in South Africa, both adopters and non-adopters. We utilized household dietary diversity score (HDDS) and the household food insecurity access score (HFIAS) to evaluate the food-nutrition security of the maize farmers.

3.3 Model specifications

3.3.1 Adoption impact of CSA on FNS of farmers (adopters and non-adopters) – The Endogenous Switching Regression Model (ESRM)

Climate change adaptation is entirely optional and is based on individual self-selection (Atta-Aidoo et al. 2022). Farmers who adopted CSA may have systematically different traits than farmers who did not adopt, and they may have decided to adapt based on anticipated net benefits (Atta-Aidoo et al. 2022). Unobservable factors of farmers and their farms may influence both adaptation decisions and food output, leading to inconsistencies in estimates of the impact of adaptation on food security (Di Falco et al. 2011). To account for selection biases, we use an endogenous switching regression model (ESRM) in adoption-decision where maize farmers confront two regimes: (1) adapt or (2) do not adapt, which are defined as follows:

$$A_i^* = Z_i\alpha + \eta_i \rightarrow A_i = \begin{cases} 1 & \text{if } A_i^* > 0, \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where farm households i choose to adopt CSA ($A_i = 1$) in response to climate change if $A_i^* > 0$, and 0 otherwise. Thus, Z denote variables that affect the expected benefits of adopting CSA.

In accordance with (Akter et al. 2023; Muñoz and Sandoval-Díaz 2023), ESRM was selected as an impact model because it can control any bias that could obscure the output. This model consists of two sections. In the first part of the model, endogeneity resulting from self-selection is estimated by a Probit regression. This determines the adoption decisions of farmers regarding CSA. In this study, the decision of a maize farmer to adopt at least one CSA technique in response to the impacts of climate change was expressed as a dummy variable (with 1 representing adopters and 0 representing non-adopters). The second section of the model depicts the CSA adopters' and non-adopters FNS determinants.

Smallholder maize farmers' likelihood of adopting a CSA increases if the anticipated benefit of adopting a CSA outweighs their likelihood of not adopting it. The expected benefits of adoption (latent variables $Y_{1i} - Y_{2i} > 0$) are higher than those of non-adoption.

The explicit formulation of ESRM is as follows:

$$\text{Regime 1 : } y_{1i} = x_{1i}\beta_1 + \varepsilon_{1i} \text{ if } A_i = 1 \text{ (adopter)} \quad (2a)$$

$$\text{Regime 2 : } y_{2i} = x_{2i}\beta_2 + \varepsilon_{2i} \text{ if } A_i = 0 \text{ (non - adopter)} \quad (2b)$$

Where Y_{1i} and Y_{2i} are the dependent variables (food-nutrition security) for adopters and non-adopters of CSA, respectively, while X' is the collective symbol for the vectors of the explanatory variables. To get a more robust identification, we employed a selection tool, as reported by (Atta-Aidoo et al. 2022; Maindi et al. 2020). Following (Gwara et al. 2022; Outhwaite et al. 2022), we used the behavioural intentions of the rural maize farmers as our selection tool. According to (Atta-Aidoo et al. 2022; Gwara et al. 2022), the factors motivating rural farmers in decision-making about adopting agricultural innovation go beyond their socioeconomic characteristics and monetary incentive but sometimes the psychological state of mind (behavioural intentions).

A farmer's behavioural intentions depict the desire and conscious decision-making process to expend effort to execute a certain strategy (Atta-Aidoo et al. 2022; Gwara et al. 2022). Having a positive behavioural intention encourages farmers to adopt new technology and increases their ability to utilize it successfully (Akano et al. 2023; Atta-Aidoo et al. 2022). This observation was also corroborated by the falsification tests (Appendix 7 and 8), where behavioural intention was adopted as a selection instrument. Following (Atta-Aidoo et al. 2022; Gwara et al. 2022), we employed selection instruments variables related to behavioural intention such as attitude, subjective norms, perceived behavioural control and intention of maize farmers to adopt CSA.

Following (Ali and Awade 2019; Issahaku and Abdulai 2020), the admissibility of these instruments is determined through a falsification test (Appendix 7 and 8). When a variable serves as a valid selection instrument, it will have a significant influence on the adoption decision of CSA; however, it will not have any significant influence on non-adopting farm households (Issahaku and Abdulai 2020). As a consequence, Appendix 7 provides evidence that the behavioural intentions of maize farmers can be regarded as reliable selection instruments because they influence the decision to adopt CSA practices. The results (Appendix 8) buttressed that the selected instrument is crucial in affecting the adoption behaviour of rural farmers in South Africa but not significant for those who did not adopt CSA.

3.3.2 Actual and counterfactual analysis: Average Treatment and Heterogeneity Effects Estimation

After employing the ESRM framework to estimate the relationship between adoption decision of CSA and FNS, we proceed to calculate the average treatment effect (ATT). This analysis, referred to as the actual-counterfactual analysis, provides estimates of the expected impacts for households that adopt CSA as well as those who do not (Akano et al. 2023; Issahaku and Abdulai 2020). Four distinct estimations are conducted: (a) the observed effect of adoption on adopters; (b) the observed effect on non-adopters (c) the hypothetical effect of adoption on non-adopters, assuming they had adopted (counterfactual); (d) the hypothetical effect of adoption on adopters, assuming they had not adopted (counterfactual). Following (Akano et al. 2023; Atta-Aidoo et al. 2022), this approach

allows us to create counterfactual outcomes for the two regimes (adopters and non-adopters), allowing us to compare the expected FNS outcomes (HDDS and HFIAS) of true adopters and their counterfactual (non-adopters). The conditional expectations for FNS in the four situations are shown in Table 1 and are defined as follows:

$$E(y_{1i}|A_i = 1) = X_{1i}\beta_1 + \sigma_{1\eta}\lambda_{1i} \quad (3a)$$

$$E(y_{2i}|A_i = 0) = X_{2i}\beta_2 + \sigma_{2\eta}\lambda_{2i} \quad (3b)$$

$$E(y_{2i}|A_i = 1) = X_{1i}\beta_2 + \sigma_{2\eta}\lambda_{1i} \quad (3c)$$

$$E(y_{1i}|A_i = 0) = X_{2i}\beta_1 + \sigma_{1\eta}\lambda_{2i} \quad (3d)$$

Consequently, the actual expectations that were seen in the sample are represented by Cases (a) and (b) along the diagonal of Table 1. While Cases (c) and (d) reflect the anticipated results of the counterfactual outcomes.

Following (Akano et al. 2023; Di Falco et al. 2011; Gwara et al. 2022), effect of treatment to adopt on treatment (TT) was measured as the difference between (a) and (c)

$$TT = E(y_{1i}|A_i = 1) - E(y_{2i}|A_i = 1) \quad (4)$$

Equation (4) denotes the impact of CSA adoption on FNS of farm households that actually adopted the practices. Additionally, we estimated the effect of treatment on the untreated (TU) for households that actually did not adopt CSA, which is represented by the difference between (d) and (b), as expressed in equation (5).

$$TU = E(y_{1i}|A_i = 0) - E(y_{2i}|A_i = 0) \quad (5)$$

Furthermore, we use the expected outcomes expressed as the difference between equation 3a–3d to calculate the heterogeneity effects (HE) shown in equation 6. Following (Antwi-Agyei et al. 2021; Di Falco et al. 2011), HE denotes the scenario whereby households that adopt CSA could experience better FNS than households that did not adopt CSA irrespective of the fact that they decided to adopt because of their unobservable characteristics such as behavioural intention (attitude, subjective norm, behavioural intention and control).

Table 1 Average Treatment and Heterogeneity Effects estimation for actual and counterfactual outcomes

Household adoption categories	Adoption decision estimations ^a		
	To adopt	Not to adopt	Treatment effects
Households that adopted	(a) $E(y_{1i} A_i = 1)$	(c) $E(y_{2i} A_i = 1)$	TT
Households that did not adopt	(b) $E(y_{1i} A_i = 0)$	(d) $E(y_{2i} A_i = 0)$	TU
Heterogeneity effects	BH ₁	BH ₂	HT

^aNoted: (a) and (b) symbolize the observed FNS, while (c) and (d) represent the counterfactual FNS of the farm households

$$HT_1 = E(y_{1i}|A_i = 1) - E(y_{1i}|A_i = 0) \quad (6)$$

Likewise, "the effect of base heterogeneity" pertains to the group of farm households that opted not to adopt; it is calculated as the discrepancy between (c) and (b), shown in equation 8.

$$HT_2 = E(y_{2i}|A_i = 1) - E(y_{2i}|A_i = 0) \quad (7)$$

Following (Antwi-Agyei et al. 2021; Di Falco et al. 2011), we examine the "transitional heterogeneity" (HT), which denotes the difference between TT and TU (i.e., equations (4) and (5)) to see if the effect of adopting CSA is larger or smaller for FNS of farm households that actually adopted CSA or counterfactual case of adoption decision.

3.3.3 Behavioural intentions of rural farmers to adopt CSA

Farmers' attitudes towards innovation and change play a significant role in their willingness to adopt sustainable agricultural practices (Gwara et al. 2022). Consequently, positive behavioural intentions toward sustainable agriculture would enhance the food security of rural households (Atta-Aidoo et al. 2022). Following (Gwara et al. 2022), the behavioural intentions of farmers to adopt CSA were based on their attitudinal dimensions assessed through 3-points Likert-scale perception statements (Table 3) with a response score of $1 < \mu < 2$. Following (Atta-Aidoo et al. 2022; Gwara et al. 2022), values obtained about the attitudinal dimensions of smallholder farmers greater than 1.5 were indicative of a positive attitude, whilst scores below 1.5, denote a negative attitude. Following (Gwara et al. 2022; Issahaku and Abdulai 2020), the attitudinal dimensions of the rural maize farmers were assessed through the following criteria (Table 3);

- i. Behavioural intention was assessed through four distinct perception statements (Table 3), aimed at investigating the farmers' decision to adopt CSA, either with or without assistance, as well as their readiness to overcome obstacles related to financial constraints and knowledge limitations.
- ii. individual attitudes towards CSA adoptions were assessed through six distinct criteria (Table 3) with three of these criteria (perception statements) specifically examining the significance, convenience, and feasibility of CSA. The remaining three criteria considered the possible advantages of CSA to enhanced crop yields, agricultural profitability, and reputation.
- iii. Subjective norm was measured with four criteria, two of which concerned the motivation to use CSA and the remaining two addressed the perceptions of others regarding the adoption of CSA.
- iv. Perceived behaviour control was assessed using four criteria. The aforementioned criteria (perception statements) pertained to the level of control that a farmer has in relation to the requisite activities involved in CSA practices.

In addition, the latent construct of CSA adoption consisted of eight items that encompassed various CSA practices in South Africa (Fig. 1); specifically, drought-tolerant varieties (DTV), cover cropping, zero/minimal tillage, mixed cropping, planting early maturing varieties (PEMV), water management/irrigation, mulching, and intercropping with legumes (IWL).

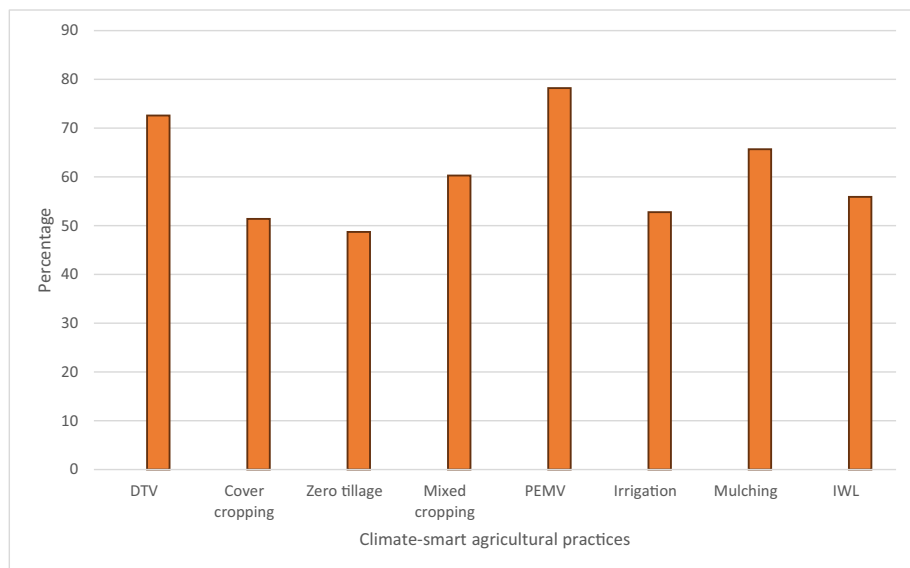


Fig. 1 CSA adopted by rural farmers in South Africa

3.3.4 Food-nutrition security (FNS) of rural farmers (adopters and non-adopters)

Given the multidimensional nature of FNS, we captured it using two measures. First, we utilize the household food insecurity access score (HFIAS) to capture the FNS. The HFIAS is a scale that quantifies and summarizes distinct behavioural and psychological dimensions of food insecurity (access) (Issahaku and Abdulai 2020). Following (Tilahun et al. 2023), households with no reported food insecurity receive a minimum score of 0 (better food access). A food-insecure household with a high frequency of ingesting less preferred foods or foregoing meals due to inadequate access to food receives a maximal score of 27. Numerous studies (Dlamini et al. 2023; Issahaku and Abdulai 2020; Popoola et al. 2022; Teklewold et al. 2019) have been done to highlight the HFIAS of rural households in South Africa (Appendix 3), but there is a dearth of knowledge on behavioural adoption-impact of CSA on HFIAS in South Africa.

The second metric is the household dietary diversity score (HDDS), which was used to measure the dietary-quality of the households. Following (Akter et al. 2023; Omotayo et al. 2022; Omotoso et al. 2022), food consumed by a household over the course of a week was classified into twelve distinct food categories, namely cereals, tubers and roots, vegetables, fruits, meat and poultry, eggs, fish, pulses and nuts, legumes, milk and milk products, oils and fats, sugar and honey, and miscellaneous items. This was used to compute the HDDS, which is a good predictor of households' nutritional status in South Africa (Appendix 4) and thus will be a relevant indicator of dietary quality at the household level (Akter et al. 2023; Omotayo et al. 2022; Omotoso et al. 2022).

4 Results and Discussions

4.1 Descriptive statistics

According to Table 2, the average age of rural farmers in our sampled survey is 47.6 years old, which reflects the vitality of South Africa's population and the region's tremendous potential for agricultural development. Recent (FAO 2021; Ricart et al. 2022) reports indicate that a larger proportion of the rural population in South Africa is over 45 years old. This indicates that individuals are expected to be productive with the resources at their disposal and conscious of their behavioural intentions toward the adoption of improved technology. The average sampled household contains 6 people, and cultivates less than 10 hectares of farmland, thus illustrating the smallholder character of agriculture in the study area (Atta-Aidoo et al. 2022; Omotayo et al. 2022).

Table 2 reveals that 87.4% of household heads possess education. Higher levels of education are indicative of robust human capital, which empowers farmers with the knowledge and skills necessary to make informed decisions regarding enhanced agricultural production practices (Bjornlund et al. 2022; Omotayo et al. 2020). With improved agricultural practices, rural farming households would experience increased crop yields and improved income generation, thereby contributing to poverty reduction and improved food-nutrition security in the households (Kangogo et al. 2021; Merga et al. 2023). Furthermore, the majority (71.9%) of rural producers interacted with extension agents. According to (Atta-Aidoo et al. 2022; Omotayo et al. 2022), contact with extension agents has a significant influence on the adoption of agricultural technology and climate change adaptation strategies among rural farm families.

Additionally, extension agents play a crucial role in the dissemination of knowledge, the provision of technical support, and the assistance of farmers in making informed decisions regarding agricultural production (FAO 2021; Ricart et al. 2022). As shown in Table 2, farm families with a greater diversity of income sources have the potential to adopt various CSAs because they have a greater diversity of resilient livelihood alternatives, which influences the behavioural decisions of households on CSA adoptions in South Africa. Similarly, remittances in the form of access to social safety will increase and diversify the sources of income for rural households, which would influence their behavioural intention towards CSA adoption in the study area.

Figure 1 illustrates the distribution of CSA adopted by smallholder maize farmers in South Africa. Farmers' comprehension of climate change has a substantial impact on their level of adaptation and the measures they take to combat the severe implications of climate change on their yields (Maindi et al. 2020; Mullins et al. 2018). Smallholder maize farmers in South Africa have devised a wide range of CSA strategies (Fig. 1) in response to the changing climate. Among them are mulching (66%), mixed cropping, zero tillage (60%), planting cover crops (51%), and irrigation (53%).

The reported HDDS of 9.10 (ranging from 2 to 11) and HFIAS of 3.412 (ranging from 1 to 25) in the previous seven days indicate that some degree of FNS exists among the studied families. Consequently, Appendix 5 and 6 depict the HFIAS and HDDS distributions of smallholder farmers, respectively, based on their adoption behaviour towards CSA. Appendix 5 revealed the HFIAS values of 2.572 and 5.145 for adopters and non-adopters' categories of smallholder farmers, respectively. Following (FAO 2021; Worku et al. 2020), these values (Appendix 5) provide insights into the extent and severity of food insecurity among rural farming households and can guide strategies and interventions to ensure food-secure

Table 2 Variable descriptions and statistical summaries used in the analysis

Variables	Descriptions	Total households		Farm households that adopted CSA		Households that did not adopt CSA	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Outcome variables							
Farm revenue	Estimated 2022/2023 agricultural season maize value per hectare (Rands/ha)	11289.551	8706.212	14895.021	9340.241	8503.732	5032.411
Household Food Insecurity Access Score (HFIAS)	An absolute food-secure HH receives a score of 0, while a completely food-insecure HH receives a score of 27	3.412	1.593	2.572	1.131	5.145	2.772
Household Dietary Diversity Score (HDDS)	Measured based on intake of 12 food groups consumed by the HH in the past 7 days	9.101	3.742	10.382	4.133	7.224	2.901
Treatment variables							
Adoption of CSA	Dummy: 1 if adopt any practices, 0 if otherwise	0.687	0.391	0.687	0.391	0.313	0.129
Socioeconomic characteristics							
Age	Actual age of household head	47.672	11.731	46.245	21.951	49.137	18.952
Gender	Dummy: 1=male, 0=female	0.751	0.393	0.812	0.573	0.288	0.115
Household size	Total members of the household	6.101	2.612	7.423	3.111	5.329	2.602
Marital status of the head	Dummy: 1 if married, 0 if otherwise	0.810	0.529	0.903	0.430	0.791	0.516
Educational status of the household head	Dummy: 1 if educated, otherwise	0.874	0.317	0.812	0.537	0.895	0.491
Years of experience	Actual year (continuous)	11.542	6.711	14.952	6.153	9.742	3.634
Off-farm income	Dummy: 1 if yes, 0 if otherwise	0.573	0.202	0.673	0.286	0.527	0.317
Contact with extension	Dummy: 1 if yes, 0 if otherwise	0.719	0.361	0.812	0.594	0.588	0.202
Land ownership	Dummy: 1 if yes, 0 if otherwise	0.675	0.442	0.778	0.345	0.573	0.202
Total land used for cultivations of other crops	Actual farm size (Continuous)	8.701	4.352	11.304	7.928	6.631	3.852
Total land used for maize cultivation	Actual land area used for maize cultivation (Continuous)	5.142	1.972	7.562	3.982	4.207	0.196
Livestock farming	Dummy: 1 if yes, 0 if otherwise	0.458	0.221	0.398	0.203	0.542	0.221

Table 2 (continued)

Variables	Descriptions	Total households		Farm households that adopted CSA		Households that did not adopt CSA	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Source of finance	Dummy; 1 if personal, 0 if otherwise	0.786	0.372	0.739	0.374	0.782	0.402
Membership of farm organization	Dummy; 1 if yes, 0 if otherwise	0.671	0.484	0.774	0.492	0.669	0.302
Access to credit	Dummy; 1 if yes, 0 if otherwise	0.381	0.130	0.118	0.183	0.487	0.205
Access to extension training	Dummy; 1= Yes to access to extension training on improved agricultural production practices, 0= otherwise	0.718	0.425	0.929	0.572	0.385	0.117
Social safety	Dummy; 1 if household members receive social grant, 0 if otherwise	0.585	0.309	0.601	0.335	0.391	0.196
Information on climate change							
Community meetings	Dummy; 1 if yes, 0 if otherwise	0.505	0.273	0.586	0.228	0.273	0.115
Flyers/Posters	Dummy; 1 if yes, 0 if otherwise	0.672	0.205	0.680	0.319	0.472	0.207
Radio	Dummy; 1 if yes, 0 if otherwise	0.791	0.289	0.927	0.504	0.305	0.135
Smartphone	Dummy; 1 if yes, 0 if otherwise	0.580	0.314	0.982	0.539	0.289	0.117
Local newspapers	Dummy; 1 if yes, 0 if otherwise	0.601	0.307	0.779	0.302	0.516	0.224
Sample size	Total number of sampled farm households	316		201 (63.6%)		115 (36.4%)	

Table 3 Summary statistics of the attitudinal dimensions of smallholder farmers

Attitudinal dimensions	Mean	Std. Dev.	Factor loading
Behavioural intention	1.651 [^]	1.021	
a. Willing to adopt CSA with or without financial support	0.613	0.225	0.201***
b. Willing to access credit to overcome financial barriers to CSA adoption	0.701	0.382	0.482***
c. Willing to source information about CSA practices	0.582	0.198	0.751***
d. Willing to learn more about CSA	0.732	0.521	0.283***
Individual attitudes	1.631 [^]	1.131	
a. CSA practices are seen as a necessary approach to improving productivity	0.850	0.392	0.503***
b. CSA practices convenient to implements	0.753	0.441	0.481***
c. CSA practices implementation on farms is practicable	0.892	0.381	0.453***
d. CSA practices will enhance farm yields	0.714	0.521	0.684***
e. CSA practices will increase farm income	0.608	0.339	0.535***
f. CSA practices will increase my reputation in the community	0.525	0.275	0.764***
Subjective norm	1.582 [^]	1.183	
a. Expected of me to adopt CSA since all other farmers have adopted it	0.587	0.207	0.571***
b. Want to be like other farmers when it comes to new technology adoption	0.612	0.406	0.661***
c. Motivation/pressure from extension agent about adopting CSA	0.784	0.372	0.345***
d. Pressure from community to adopt since others have already adopted CSA	0.550	0.185	0.226***
Perceived behaviour control	1.433 [^]	1.072	
a. I am able to practice at least one of the CSA practices	0.504	0.202	0.574***
b. Resources to implement CSA practices on farms are available	0.408	0.198	0.820***
c. All the information needed to adopt CSA has been provided	0.536	0.275	0.421***
d. Risky and unprofessional	0.525	0.176	0.304***

Note: *** significant at 1%; [^] weighted mean score (for constructed attitude)

households by 2030. Appendix 6 depicts the HDDS values of 10.382 and 7.224 for adopters and non-adopters' categories of smallholder farmers, respectively. HDDS values have implications for FNS and agricultural planning, aligning with the goals and objectives of FAO and other organizations working to improve global food security and nutrition outcomes. Interestingly, the findings indicate that the implementation of CSA practices by smallholder farmers has the potential to significantly enhance FNS in South Africa. In general, a rise in HDDS indicates an improvement in the household's dietary quality and nutrition security, while a drop in HFIAS indicates an improvement in the household's access to food (Omotayo et al. 2022; Pawlak and Kołodziejczak 2020).

4.2 Behavioural dimensions of rural farmers toward the adoption of CSA practices

The confirmatory factor analysis (Table 3) demonstrates that the observed variables highlighted were significant ($p < 0.01$) and deemed adequate to explain the behaviour intentions of the farmers, with values ranging from 0.201 to 0.820. Additionally, it depicts that all four constructs - individual attitude, subjective norm, perceived behaviour control, and behavioural intention of rural farmers' behavioural dimensions

assessed through 3-points Likert-scale perception statements were significant (Table 3). Thus, denoting that they were internally consistent and reliable for assessing maize farmers' behavioural attitudes toward CSA adoption in South Africa. The behaviour intention score was favourable (1.651), showing that farmers were eager to adopt CSA in farming operations. The individual attitude score also denotes a positive response (1.631) to the adoption of CSA.

Consequently, the subjective norms were not as dissuasive as the other behaviour dimension (1.582), which showed that farmers would adopt CSA if the benefit of CSA adoptions was well established by other farmers. Potential hurdles were indicated by perceived behavioural control (1.433), which showed that farmers thought adopting CSA in agriculture was risky and that they lacked the necessary skills and self-efficacy to utilize it. This research was in accordance with (Atta-Aidoo et al. 2022; Gwara et al. 2022; Mutengwa et al. 2023), reported that not only financial incentives can motivate farmers' adoption behaviour, but the behavioural dimension has also been useful in illuminating farmers' decision-making processes. This is due to the fact that farmers aren't only profit-maximizing entities, but may also be impacted by other intrinsic and human incentives, particularly when a choice might have social and environmental repercussions.

The result predicts farmers' attitudes towards CSA adoptions on the supposition that their behavioural attitudes, which govern their adoption-decisions, are influenced by individual attitudes, subjective norms, perceived behavioural control and intentions. The analysis revealed a noteworthy and statistically significant correlation between the attitude of farmers and their inclination to embrace CSA. The results obtained in this study align with the conclusions drawn in other research (Atta-Aidoo et al. 2022; Gwara et al. 2022; Mutengwa et al. 2023), indicating that behavioural intentions serve as the most effective first factor for initiating the decision-making process. The influence of farmers' mindset on behavioural dimension towards conservation agriculture has been documented by (Kangogo et al. 2021; Maindi et al. 2020; Mullins et al. 2018), revealed that behavioural intention has a significant role in influencing rural maize farmers' decision-making in adopting new technology, which would have a significant impact on their households' FNS.

4.3 Empirical analysis of the determinants of CSA adoption – ESRM

The outcomes of the empirical analysis of ESRM are presented in this section. To begin, we investigated the determinants that impact the CSA adoption. As previously stated, the ESRM estimates two distinct but related outcome equations, one for each group (adopters and non-adopters), in conjunction with an adoption selection equation. The second estimate revealed the determinants of FNS outcomes (HDDS, and HFIAS) for smallholder maize farmers.

The joint independence equation's likelihood ratio test (LR test) is statistically significant at the 1% level. Consequently, we conclude that the models should not be evaluated independently, as they are mutually dependent. Additionally, we noticed that both covariances (σ_1 , and σ_2) deviate from zero, indicating the presence of endogeneity (Ali and Awade 2019); this further supports the usage of the ESRM. Furthermore, the correlation coefficients ρ_1 and ρ_2 of the adopter models are statistically significant at 1%. This implies that individuals who choose to adopt CSA experience better HDDS and HFIAS than non-adopters of CSA in the study area.

4.3.1 Drivers of adoption of CSA - First stage ESRM

The adoption predictors of CSA by smallholder farmers in South Africa are shown in the second column of Table 4, illustrating the obtained findings. In general, the findings indicate that the adoption of CSA is significantly influenced by household factors (education level, household size, and sex), resource restrictions (farm size, access to credit, and off-farm income), institution variables (access to extension training, members of cooperative society, and sources of climate information – radio, smartphones, and community meetings), and the perceived attitudinal dimensions (individual attitude, subjective norms, behaviour intention, and control) of the smallholder maize farmers.

The coefficient for the household size variable is positive and substantially distinct from zero, suggesting that households with a larger prospective labour force are more likely to employ CSA. The coefficient for the variable education is also positive and substantially distinct from zero, suggesting that producers with a higher level of education are more likely to implement CSA. According to (Akpan and Zikos 2023; Omotoso et al. 2022), education helps farm families grasp the benefits of new agricultural technology by boosting awareness and improving adoption decisions. The adoption of CSA is more prevalent among female farmers, as seen by the statistically significant negative coefficient associated with the gender variable, a result that aligns with (Aidoo et al. 2021; Popoola et al. 2022) findings. Off-farm income is also a significant variable that influences the adoption of CSA suggesting that adoption decision on farm and off-farm income activities are complementary. This suggests that engaging in off-farm income-generating activities liberates farmers from financial constraints that might prevent them from implementing new agricultural technology (Daud et al. 2018; Kangogo et al. 2021).

Another intriguing finding is the estimate of access to extension variable. We discovered that farmers' extension interactions improve their likelihood of adoption. Farmers may acquire relevant information regarding climate-smart practices via extension contacts. Similarly, (Daud et al. 2018; Kangogo et al. 2021), posited that rural households' confidence in the abilities of extension agents has a significant influence on their propensity to employ agricultural technologies. CSA adoption was shown to have a favourable correlation with increased access to climate information through radio, community meetings and smartphones. This suggests that the respondents would be more likely to use adaptation techniques if they had appropriate awareness about climate change. The adoption of CSA was also found to be positively correlated with membership in agricultural cooperatives. According to (Akpan and Zikos 2023; Omotoso et al. 2022), membership in agricultural cooperative societies has a positive and statistically significant impact on the adoption of agricultural technology and the productivity of the maize farming households.

Cooperatives facilitate member access to inputs, credit, and markets (Akpan and Zikos 2023; Daud et al. 2018; Omotoso et al. 2022). The results also demonstrated that South African smallholder farmers with constrained credit access are less likely to adopt CSA. This implies that the adoption of novel agricultural technologies requires a monetary investment. Prior research (Omotayo et al. 2022; Pawlak and Kołodziejczak 2020), has demonstrated that rural households are more likely to implement agriculture innovations if they have access to credit. Additionally, this study discovered a consistent positive influence of the behavioural attitude of rural farmers on CSA adoptions in South Africa. This could be attributed to the endogeneity of the behavioural dimension

Table 4 Determinants of CSA adoption and HHDS and HFIAS of adopters and non-adopters

Variables	CSA adoption	HHDS		HFIAS	
		Adopters	Non-adopters	Adopters	Non-adopters
Constant	0.125*** (0.055)	0.365*** (0.101)	0.561*** (0.129)	0.278*** (0.087)	0.056 (0.049)
Age	0.296*** (0.103)	-0.387 (0.853)	0.154 (0.164)	0.175 (0.243)	0.040* (0.022)
Gender	-0.075*** (0.038)	-0.056*** (0.022)	-0.186 (0.264)	0.198*** (0.058)	-0.111 (0.085)
Household size	0.115*** (0.031)	-0.152* (0.080)	0.063 (0.321)	0.088* (0.047)	0.105 (0.096)
Marital status of the head	-0.116 (0.283)	0.187 (0.439)	-0.107*** (0.040)	0.190 (0.165)	0.724 (0.773)
Educational status of the household head	0.198*** (0.053)	0.036*** (0.018)	0.147* (0.081)	0.065 (0.109)	-0.476 (0.392)
Years of experience	0.286 (0.789)	0.368 (0.472)	0.075 (0.379)	0.308 (0.281)	0.197 (0.209)
Off-farm income	0.387*** (0.092)	0.037*** (0.018)	0.078 (0.195)	-0.157*** (0.082)	0.050 (0.103)
Contact with extension	0.043** (0.022)	0.177*** (0.082)	0.186 (0.291)	-0.082*** (0.041)	0.272 (0.185)
Land ownership	-0.184 (0.263)	-0.178 (0.654)	0.306*** (0.101)	0.074 (0.106)	0.007 (0.013)
Total land used for cultivations of other crops	0.459 (0.653)	0.642 (0.539)	-0.007 (0.038)	0.039 (0.051)	-0.602 (0.592)
Total land used for maize cultivation	-0.096 (0.185)	-0.363 (0.378)	0.023** (0.011)	0.178 (0.195)	0.102** (0.049)
Livestock farming	0.187 (0.259)	0.439 (0.653)	0.017 (0.018)	0.209 (0.194)	-0.012 (0.028)
Source of finance	-0.471 (0.389)	0.153 (0.118)	-0.188 (0.175)	0.059 (0.104)	0.307 (0.294)
Membership of co operative organization	0.183* (0.097)	-0.276 (0.197)	0.907 (0.865)	0.204 (0.213)	0.018 (0.175)
Access to credit	0.049* (0.026)	0.086** (0.043)	-0.084 (0.175)	-0.609 (0.421)	0.028** (0.011)
Access to extension training	0.654*** (0.307)	0.209*** (0.097)	0.261 (0.334)	-0.056*** (0.021)	-0.037 (0.164)
Radio	0.034*** (0.015)	0.981*** (0.321)	-0.085 (0.155)	-0.106* (0.062)	0.098 (0.082)
Smartphones	0.007*** (0.003)	0.159*** (0.045)	0.032 (0.186)	-0.087* (0.047)	-0.027 (0.118)
Community meetings	0.208*** (0.097)	0.226** (0.096)	0.024 (0.183)	-0.102*** (0.051)	0.197 (0.229)
Flyers/Posters	0.872 (0.923)	0.006 (0.108)	0.107 (0.098)	0.046 (0.078)	-0.106 (0.140)
Local newspaper	0.112 (0.108)	0.048 (0.113)	0.038 (0.011)	-0.085 (0.118)	0.088* (0.047)
Social safety	-0.184 (0.181)	0.108 (0.265)	0.096 (0.165)	-0.004 (0.013)	0.066*** (0.029)
Behaviour intention	0.052*** (0.028)				
Individual attitude	0.116*** (0.031)				

Table 4 (continued)

Variables	CSA adoption	HDDS		HFIAS	
		Adopters	Non-adopters	Adopters	Non-adopters
Subjective norms	0.024** (0.010)				
Behavioural control	0.011* (0.006)				
Sigma_1		0.037*** (0.011)	0.112 (0.099)	0.086** (0.039)	0.054 (0.103)
Sigma_2		0.175*** (0.082)	0.088 (0.125)	0.105*** (0.053)	0.149 (0.184)
Rho_1		0.184*** (0.028)	0.033 (0.105)	-0.158 (0.103)	-0.107 (0.099)
Rho_2		0.095*** (0.031)	-0.164 (0.119)	-0.078** (0.022)	0.072 (0.102)
Wald test χ^2 (75) = 198.67, $p < 0.001$,					
Log-likelihood = -285.402					
LR test of independent equations χ^2 (2) = 28.15***					

Note: *, **, and *** denotes 10%, 5%, and 1% significance level, respectively
Values in parentheses are robust standard error

of smallholder farmers in the propagation of CSA practice. Due to fact that CSA are frequently knowledge-intensive and require reassurance regarding usage and management procedures, therefore smallholder maize farmers' positive attitude play a significant role in CSA adoption in South Africa.

Consequently, the presence of positive and statistically significant correlations between the adoption of CSA and farmers' behavioural intention suggests that holding favourable attitudes about CSA enhances the likelihood of farmers intending to adopt these practices. The development of favourable attitudes towards CSA practices is contingent upon farmers seeing the favourable effects that CSA practices have on agricultural productivity and households' food-nutrition outcomes (Atta-Aidoo et al. 2022; Gwara et al. 2022; Mutengwa et al. 2023). Specifically, it was found that individual attitude, subjective norms and behavioural intentions have been the most substantially behavioural intentions influencing farmers' decision-making in adoption of CSA. This also verifies the validity of the ESRM model's instrumental variable (behavioural dimension of the smallholder maize farmers – behavioural intention, individual attitude, subjective norms and behaviour control).

4.3.2 Determinants of HDDS and HFIAS of adopter and non-adopter of CSA

The column 3 and 4 (Table 4) displays the HDDS and HFIAS determinants for adopters and non-adopters of CSA. As reported, certain important household characteristics (household size, gender, and off-farm income) are notably significant in the HDDS and HFIAS outcomes. In the HDDS outcomes, coefficient associated with household size negative and demonstrate statistical significance for adopters of CSA while positive and statistically significant for HFIAS outcome, indicating that, all other things being equal, a larger family size is associated with poor dietary quality. The positive and statistically significant coefficient of the variable representing education suggests that a higher level of education may be associated with a higher HDDS intake. This is consistent with earlier research that found a positive and statistically significant correlation between household education and dietary quality (Jellason et al. 2021; Omotayo et al. 2022). This could be attributed to fact that education improves the maize farmers' understanding of food and nutrition security (Kangogo et al. 2021; Omotoso and Omotayo 2024a).

The coefficient associated with gender variable is statistically significant (negative for HDDS and positive for HFIAS), indicating that female-headed households are associated with increased dietary diversity among adopters. This finding aligns with previous research that linked empowered female household heads to heightened dietary diversity in SSA (Akter et al. 2023; Asravor 2022). It is important to note that in many regions of Africa, women are typically in control of food preparation and therefore tend to influence dietary quality. This finding reaffirms the importance of gender in food and nutrition security, as outlined in the South Africa National Food-Nutrition Policy for 2023.

The coefficient associated with off-farm employment has a positive relationship with the HDDS but a negative relationship with the HFIAS. Moreover, this coefficient is statistically significant, suggesting that involvement in off-farm employment is likely to result in enhanced dietary variety and quality (HDDS) as well as improved access to food (HFIAS). The observed results may be attributed to the income effect stemming from engagement in non-farm work, whereby families use their earnings from non-farm employment to improve their food-nutrition security. Access to credit has a significant effect on HDDS but not on HFIAS. Intriguingly, extension contact and extension training have the anticipated

indications in both HDDS and HFIAS, indicating that extension service plays a significant role in enhancing food-nutrition security in South Africa.

4.4 Average Treatment (ATT) and Heterogeneity Effects Estimation - Impacts of CSA Adoption on HDDS and HFIAS

The primary aim of this study is to assess the impact of implementing CSA on the results related to the FNS (HDDS and HFIAS) of rural farm households in South Africa. The ESRM allows for the acquisition of anticipated results pertaining to FNS, contingent upon the adoption of CSA (Ewunetu et al. 2023). The term "average treatment effect on the treated" refers to the discrepancy between the expected output of those who have chosen to adopt (adopters) and the counterfactual outcomes if they had not made that decision (non-adopters) (Ewunetu et al. 2023; Njuguna et al. 2022). The average treatment effect and heterogeneity of CSA adoption on household food-nutrition security in South Africa are shown in Table 5. Noteworthy, heterogeneity effects, which account for the potential heterogeneity in the sample rural households, indicate that in the counterfactual case, maize farming households that adopted CSA would have produced considerably more than those that did not adopt CSA. This observation highlights the presence of significant heterogeneity factors that distinguish adopters as "better food-secure households" than non-adaptors, in the context of the climate change issue. Despite this, maize farming households in South Africa that adopted CSA still experienced a better FNS than those that did not.

The result presented in Table 5 indicates that household heads who adopt CSA observed a 3.156 (27%) increase in HDDS compared to those who do not adopt CSA practices. Subsequently, HDDS would have increased by 2.115 (23%) had non-adopters implemented CSA practices. The outcome illustrates that the adoption of CSA practices substantially raises the HDDS of rural farming households in South Africa. The results are comparable to those of (Akano et al. 2023; Antwi-Agyei et al. 2021; Di Falco et al. 2011), who discovered that the HDDS of rural farmers in SSA was enhanced by adopting CSA practices. Additionally, the result demonstrates that the adoption of CSA practices has also yielded a noteworthy impact in mitigating the extent of food insecurity within rural maize farming households in South Africa.

Interestingly, adopting CSA practices decreases the probability of household food insufficiency and HDDS by 2.576 (35%). The household food gap and HFIAS would have been

Table 5 Average Treatment and Heterogeneity Effects estimation for actual and counterfactual FNS (HDDS and HFAS) outcomes

FNS outcomes		Adoption decision estimations		
		To adopt	Not to adopt	Treatment effects
HDDS	Adopters	9.177 (4.036)	6.021 (3.011)	3.156*** (1.024)
	Non-adopters	7.265 (2.861)	5.149 (2.853)	2.115*** (0.087)
	Heterogeneity effects	-1.852*** (0.372)	0.872*** (0.211)	1.041** (0.578)
HFIAS	Adopters	2.851 (1.962)	5.427 (2.439)	-2.576*** (0.073)
	Non-adopters	4.702 (1.628)	8.217 (3.872)	-3.515*** (1.003)
	Heterogeneity effects	1.851	-2.790	-0.939*** (0.124)

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

reduced by 3.515 (41%) if non-adopters had implemented CSA practices on their farm. Consistently, CSA practices contributes to the resilience of ecosystems, making smallholder farmers less susceptible to extreme weather events and other climate-related challenges, optimizing agricultural productivity, and reducing the risk of food insufficiency (Ali et al. 2020; Omotoso and Omotayo 2024b). By adopting practices that make agriculture more resilient to climate-related challenges, households are better positioned to maintain stable food production despite environmental variations. Thus, higher crop yields contribute to increased food availability within the household, reducing the likelihood of food shortages and improving overall food security (Hasan et al. 2018). Consequently, the results of the study confirmed that the adoption of CSA substantially improved household food-nutrition security (as measured by the household dietary diversity score and the household food insecurity access score). Recent empirical research conducted by (Ewunetu et al. 2023; Njuguna et al. 2022) bears resemblance to the current investigation, which revealed that the adoption of CSA practices such as crop diversification, soil and water management resulted in greater utility returns for rural households' welfare.

5 Conclusion and policy implication

This research investigates the behavioural intentions of smallholder maize farmers to implement CSA practices and the subsequent impacts of adoption on food-nutrition security (HDDS and HFIAS) outcomes in South Africa. The study made use of cross-sectional data obtained via field surveys from rural farmers in South Africa. We used ESRM to address a possible selection bias that may result from both observable and unobserved sources. Furthermore, we conducted an estimation of the impacts of adoption on FNS (proxied by HDDS and HFIAS) outcomes to evaluate the distributional consequences of adoption. The present study has presented empirical data on the influence of individual attitude, subjective norm, perceived behaviour intention, and control on the intentions and eventual adoption of CSA practices among rural maize farmers in South Africa. The findings indicate that there is a positive correlation between behavioural attitude of farmers and their adoption decisions about implementing CSA on their farm. Furthermore, ESRM indicates that there are some household characteristics (age, household size, and educational status), farm-level factors (off-farm income, and access to credit), and institutional factors (access to extension training on improved agricultural practices, and climate information through radio, phones and community meetings) that have a substantial impact on farmers' choices to adopt CSA. Consequently, behavioural intentions (such as subjective norms, individual attitudes, and behavioural control) positively and significantly influence CSA adoption by smallholder maize farmers in South Africa. Additionally, the adoption of CSA had positive and significant impacts on the FNS of smallholder farmers. The result herewith depicts that CSA adoption increases the HDDS of rural farmers by 23% and decreases their HFIAS by 35%. The study concluded that farmers who cultivate a more positive attitudinal dimension are more likely to enhance their desire to implement CSA practices. Overall, given that farmers' attitudinal dimension towards CSA adoption is linked to improvement in agricultural productivity, we draw the conclusion that it is responsive to the FNS of smallholder maize farmers in South Africa. Therefore, policy interventions should be focused on raising awareness among rural farmers in order to foster a more favourable attitude towards CSA practices. Farmers' favourable behavioural intentions toward CSA practices could be enhanced through the updated extension services and the integration of climate change

sensitization into the extension delivery method through radio, smartphones, local newspapers and flyers or posters. This would boost the adoption of climate-smart practices, hence improving the resilience of farmers to climate change and FNS in rural households. Furthermore, future perspectives in this field should aim to address emerging challenges, embrace technological advancements, and contribute to the development of sustainable and climate-resilient agricultural systems among the rural maize farmers. Additionally, collaborative efforts involving researchers, policymakers, and local communities will be essential for shaping a more sustainable and food-secure future in the face of climate change.

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

Declarations

Ethical standard The Ethics Committee of the Faculty of Natural and Agricultural Sciences at North-West University in South Africa approved the research's ethical clearance (NWU-01267-23-A9). While the Department of Rural, Environment and Agricultural Development, NW, South Africa, granted the researchers permission to visit the study area.

Consent to participate This was asked from the participants before the survey was carried out

Consent for publication Not applicable

Conflict of interest The authors declare that they are unaware of any known competing financial interests or personal relationships that would influence the presentation of the information in this paper and its content.

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