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The Food Security Impact of Climate-Smart Agricultural Technologies Adoption on Smallholder Farmers in West Africa Sahel Region

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Abstract

Climate change remains a major impediment to food security in majority of developing countries, such as the West Africa Sahel (WASR), due to the rudimentary and rain-fed production system practiced by most farmers. The adoption of climate-smart agricultural technologies (CSAT), which aim to increase resilience and adaptation to changing climatic conditions, is crucial for boosting crop productivity and increasing food sufficiency. This study examined the food security impact of smallholder farmers adopting CSAT in WASR (Mali and Niger). We control for potential endogeneity bias that could occur in this study by employing the extended ordered probit and multinomial endogenous treatment effect model to analyze food security impact using the two most common approaches, which are the Household Food Insecurity Access Scale (HFIAS) and Food Consumption Scores (FCS). The impact results from the HFIAS estimation indicate that CSAT adopters are more food insecure than non-adopters in WASR. Subsequently, the FCS estimation results show that smallholder farmers adopting CSAT are less food secure than non-adopters. Further analysis of mechanisms and pathways to food security revealed that CSAT adopters significantly reduced the share of crop production they retained for household consumption compared to non-adopters. Subsequent findings revealed that adopters of CSAT generate significantly higher crop revenues than non-adopters. This implies that CSAT adopters sell the majority of their marketable surplus and retain a minor share for household consumption. These findings suggest that farm-level sensitization programs could emphasize the need for farmers to strike a balance between agricultural investment and food security.

JEL Codes: 033 Q16 Q54

1. Introduction

In recent years, the impacts of global climate change on food production and distribution have been more obvious, particularly in the global south. Climate change is, therefore, considered to be one of several interrelated trends and hazards that pose challenges to agriculture and food systems. According to the findings of Myers et al. (2017), it is evident that there are growing constraints on our capacity to allocate additional land, water, or fishery resources to meet the escalating global food requirements. Climate change is associated with increasing temperatures and heightened precipitation, potentially altering the interactions among crops, pests, pathogens, and weeds (Skendžić et al., 2021). Additionally, it amplifies several patterns, like the decrease in pollinating insects, the increasing scarcity of water, the rise in ground-level ozone concentrations, and the extinction of fisheries (Bajwa et al., 2020). Based on the prevailing projections of future climate change, it is widely expected that the warming phenomenon will generally lead to a decrease in the productivity of significant staple crops such as maize and wheat. This effect is particularly pronounced in tropical regions, where more substantial declines in agricultural yields are anticipated (Zougmoré et al., 2021).

The vulnerability of low-income food producers and consumers in sub-Saharan Africa (SSA) to climate change is anticipated to be higher due to their more constrained capacity to invest in adaptive institutions and technology amidst escalating climatic threats (Akampumuza et al., 2020; Anim et al., 2022). Furthermore, as stated by the Food and Agriculture Organization (FAO, 2018), climate change is projected to result in a population of 71 million individuals experiencing food insecurity, and approximately half of these individuals are expected to reside in SSA. The adverse effects of climate change are compounded by additional challenges such as unemployment, reduced income, inadequate nutrition, diminished well-being, land degradation, disruption of natural ecosystems, and an escalation in conflicts. Nevertheless, our current approach is insufficient in terms of effectively developing the capacity of smallholder farmers in SSA to withstand and recover from severe occurrences within a limited timeframe (Cuaresma et al., 2018). Hence, there is an increased urgency to modify the management of food systems in order to expedite the attainment of food security and sustainable development.

Various conventional strategies, including crop modification, alterations in field management systems, and the implementation of climate-smart agricultural practices/technologies (CSAT), can be employed to mitigate the issue of food insecurity in the context of climate change. CSAT has emerged as a viable adaptation strategy in developing regions, attracting considerable scholarly attention in recent years (Bazzana et al., 2022; Javed et al., 2022; Tesfaye et al., 2018). CSAT pertains to an agricultural approach that aims to sustainably raise productivity, bolster resilience in the face of climate change, mitigate greenhouse gas emissions, and contribute to the attainment of national food security and development objectives (FAO, 2010). CSAT has been put out as a viable approach to revolutionize agricultural systems in order to effectively address the challenges of climate change and ensure food security (CCAFS, 2022).

The Sahel region in West Africa exhibits distinct features such as a semi-arid climate, pronounced susceptibility to climate change, and a notable reliance on rainfed agriculture as a primary means of sustenance. The region's food security faces significant problems due to the combination of weather instability and increasing population demands. Due to the escalation in global temperatures and the consequent irregular weather patterns, the subsistence farming populations in the Sahel region are confronted with heightened risks of crop failure, diminished yields, and instability in their livelihoods. Within this particular environment, it is of utmost importance to prioritize the implementation of CSAT as a strategy to improve both agricultural output and household food security. CSAT involve a diverse array of strategies and methods that are designed to effectively tackle the issues presented by climate change, while simultaneously promoting sustainable agricultural production (CCAFS, 2022). These practices encompass a range of strategies such as enhanced soil and water management, diversification of crops, implementation of agroforestry techniques, efficient utilization of irrigation systems, and the adoption of crop types that are resilient to drought, among other measures (Awotide et al., 2022; Olayide et al., 2020; Zakari et al., 2022; Zegeye et al., 2022).

Ever since its introduction as an innovative approach to guide agricultural investments in a changing environment, CSAT has been a subject of interest for several empirical studies. The study conducted by Awotide et al. (2022) examined the effects of CSAT on household welfare in Mali, revealing a positive impact of CSAT on welfare outcomes. In a study conducted by Assefa et al. (2021), the authors investigated the effects of CSAT bundle packages on agricultural yields in Ethiopia. Their findings indicated that the implementation of many practices inside these bundles did not necessarily result in enhanced crop yields. In a similar context, the study conducted by Ojo and Baiyegunhi (2020) examined the impact of climate adaptation techniques on the farm income of small-scale rice farmers in Southwest Nigeria. The findings indicated that those who implemented climate adaptation strategies experienced a greater net farm income in comparison to their counterparts who did not adopt such strategies. Most of these studies have focused on a single-crop specific (usually rice or maize) and conducted in diverse agroecological areas of SSA.

Therefore, even though there has been advocacy for the adoption of CSAT practices as viable solutions, there is still a lack of comprehensive understanding of their actual impact on improving household food security within the context of a multi-cropping system prevalent in the Sahel region. Moreover, the intricate socio-economic and cultural circumstances within Sahelian communities give rise to subtleties that might either help or impede the adoption and application of these practices. In addition, it is necessary to analyze the possible trade-offs and synergies between the changes necessitated by CSAT, such as alterations in conventional farming techniques, land tenure systems, and resource accessibility, among others, in relation to the overarching objective of improving food security. In the absence of an in-depth understanding of these processes, initiatives targeted at fostering CSAT adoption may unintentionally amplify pre-existing disparities or fall short of achieving the expected advantages.

Hence, this study aims to fill a substantial gap in information by employing a rigorous quantitative analysis to undertake a thorough evaluation of the impacts of CSAT on household food security in the Sahel regions of West Africa, specifically Mali and Niger. This study focuses on CSAT adoption in a multiple and categorical order. Specifically, three main CSAT adopters are considered; 1. farmers who adopt one CSAT components, 2. farmers adopting any two CSAT components and 3. farmers adopting all three components of CSAT. These categories of CSAT adopters are compared with non-CSAT adopters for our analysis. The CSAT components considered in the study are improved crop varieties, agrochemicals (chemical fertilizers, herbicides and insecticides) and sustainable land management practices/technologies (which include soil and water conservation, agroforestry, and improved fallows, among others).

2. Household food security measurement

Among the most widely used and acceptable measurements for household food security are the Household Food Insecurity Access Scale (HFIAS) and Household Food Consumption Score (HFCS)[1]. The HFIAS is based on subjective measurement, while the HFCS is an objective measurement of food security.

2.1 Household Food Insecurity Access Scale (HFIAS)

The HFIAS is a food (in)security component where questions related to food deprivation experience in the household are inquired about. In this study, the HFIAS is constructed by the farm household head answering eight multiples YES or NO questions about their experience regarding access to food in the previous month. The YES takes a value of 1 if the farmer has a challenge regarding the food security question, and NO takes a value of 0 if otherwise. The summation of these questions (values) is termed the HFIAS score. Thus, the higher the HFIAS score, the higher the food insecurity status of the farm household. We further disentangle the HFIAS into four main categories (Food secure=1, mildly insecure=2, moderately insecure=3, severely insecure=4) to measure the level of food (in)security among the farm household as shown in Figure 1.

[1] HFIAS was developed by the Food and Nutrition Technical Assistance (FANTA) project of the United State Agency for International Development while the HFSC was developed by the World food Program. See Coates et al. (2007) and WFP (2008) for detailed information on HFIAS and HFSC.

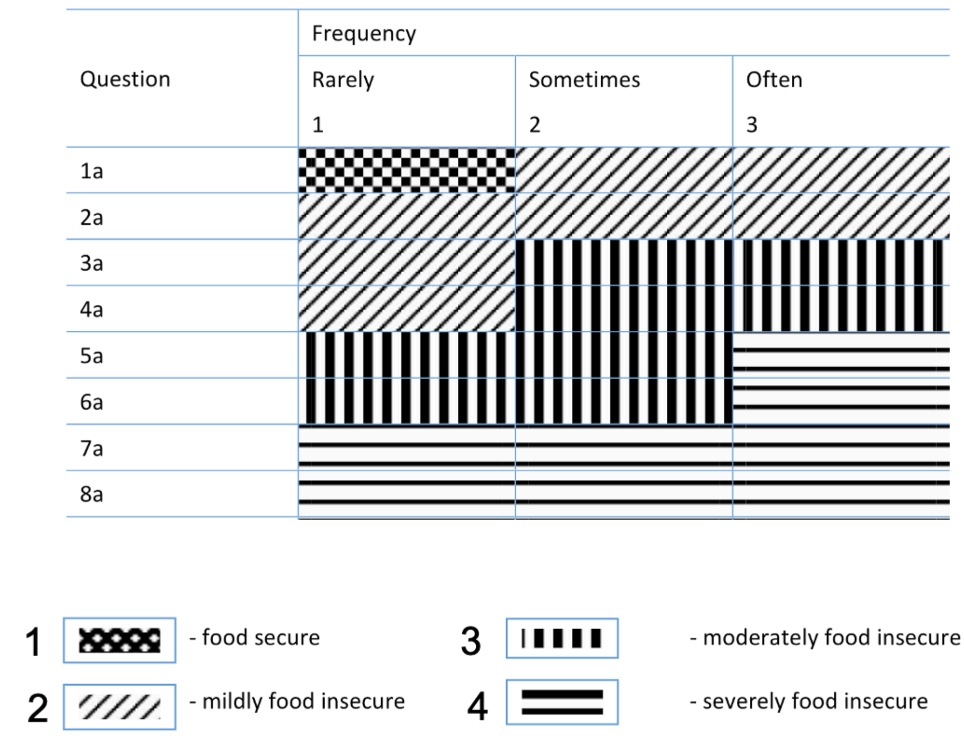

Figure 1. Household food insecurity access categories

Source: Adapted from Coates et al. (2007)

2.2 Household Food Consumption Score (HFCS)

The HFCS is a form of dietary diversity that summarizes different intervals of varieties of food groups consumed in the previous seven days by a household. The HFCS considered in this study is constructed based on food groups that are consumed in major SSA countries, including Mali and Niger. The HFCS was computed by summing the frequencies of different weights of food groups consumed in a household in the past seven days. The values take a range between 0-7 for consumption frequencies of food products in the same group. All values above seven were benchmarked to seven for each food group. The summation of the weighted food group scores generated the HFCS. For HFCS, the more diversified the food groups and weights, the higher the HFCS (i.e. food security status) of the farm household. Similar to HFIAS, we disentangle the HFCS into three categories: acceptable =1 (if HFCS>35), borderline=2 (if HFCS = 21.5-35) and poor=3 (if HFCS=1-21).

3 Methodology

3.1.1 Study area and sampling technique

This study focuses on two vital countries (Mali and Niger) in the WASR that are currently among the most adversely affected by climate change in SSA. Mali and Niger are neighbouring landlocked countries that experience similar climatic conditions. The three main climatic zones in these countries are the Saharan desert, Sahel, and Sudan climate. Agriculture (crop production and livestock rearing) is the most prevalent occupation and source of income in both countries. Most of the inhabitants are rural dwellers who are engaged in farming and herding.

We utilize cross-sectional baseline survey data collected in 2019 by the International Institute of Tropical Agriculture (IITA), social science and agribusiness department, Bamako, Mali. A multistage random sampling was used to select regions, communes and farm households for both Mali and Niger. The first stage involved the purposive selection of four major crop production regions2 in Mali and Niger. These regions were selected based on the agroecological condition, cropping intensity, accessibility and security. The main crops produced in the selected regions include cowpea, groundnut, millet, maize, rice, sorghum, soybean, and vegetables.

Subsequent stages involved a random selection of 32 communes and 320 villages in each country. About seven smallholder farm households per village were selected for the survey using a well-structured and standardized survey tool. A pre-test was done using two close villages, to ascertain the reliability of the survey instrument by trained enumerators and supervisors who are also fluent in the local language of the farmers. The pre-test experience was used to address the requirement for extra questions and fix all the reported issues. The data set contains a total of over 4000 farm households. We selected 3371 smallholder farm households (2004 in Mali and 1367 in Niger) that cultivated the five staple crops (millet, sorghum, cowpea, groundnut, and maize) for our study.

3.1.2 Conceptual and empirical framework

In this study, the main objective is to estimate the causal impact of CSAT adoption on the food security status of farm households in Mali and Niger. Thus, estimating technology adoption impacts requires a reliable econometric approach

[2] The selected regions in Mali are Kayes, Koulikoro, Sikasso and Segou while those in Niger are Tillabery, Dosso, Maradi and Zinder.

to control for issues such as self-selection. In our study, the adopters of CSAT are not selected randomly; therefore, CSAT adopters might decide to utilize the technology based on both observable (such as social and human capital and resource accumulations) and non-observable (e.g. passion, managerial skills) characteristics. This could influence the adoption of CSAT and the food security status of the farm households.

This study employs two methods to deal with the issue of endogeneity, based on the outcome variables of interest. First, for the ordered (categorical) form of both treatment and outcome variables, we utilize the extended ordered probit (EOP) regression approach. Secondly, the multinomial endogenous treatment effect (METE) approach, was used as a robustness check for the continuous outcome variables. Both approaches are suitable for capturing multiple treatment and outcome variables in a model. These methods are discussed vividly in the subsequent sub-section.

3.1.2.1 Extended ordered probit regression

The extended ordered probit (EOP) regression is an extension of the traditionally ordered probit (OP); the EOP complements the OP by its' ability to estimate the treatment effects of ordered outcomes. The number of CSAT components adopted and categories of food security measurements (HFIAS and HFCS) are considered ordinal variables for estimation in the EOP model. The EOP follows an OP model, as discussed earlier in a utility framework. Thus, farmers' decision to adopt CSAT is based on expected benefits such as improving food security status. This utility can be expressed as;

$$t_i = z_{ti}\alpha_t + e_{ti} \tag{1}$$

$$t_i = \omega_h \quad \text{iff} \quad k_{h-1} < z_{ti}\alpha_t + e_{ti} < k_h$$

where t_i denotes the treatment variable of CSAT adoption of an ith farmer and ω_h is the CSAT components order i.e. h=0,1,2,3 for non-adoption, adoption of one CSAT, two CSAT, and all three CSAT components, respectively. Z_i are set of exogenous variables, α_t vector of parameter estimates and e_i is the unobserved error term. The food security outcome can be observed as;

$$F_{ji}^* = x_i\beta_j + e_{ji}, \quad j = 1, \ldots \ldots . . J \quad \text{if } t_i = 1,\ 2 \ldots . . J$$

$$F_i = \sum_{j=1}^{T} 1\left(t_i = \omega_{tj}\right) F_{ji} \tag{2}$$

The F_{ji} represents indicators of food security (i.e. HFIAS and HFCS), the subscript j represents the different categories of HFIAS (j= 1,2,3 and 4 for food secure, mildly insecure, moderately insecure, and severely insecure) and HFCS (j= 1,2, and 3 for acceptable, borderline and poor food consumption levels) the vector x is the same with z in equation 1 but excludes variables that are used for identification in the EOP model[3]. β_j denotes an estimated parameter, and e_i is the error term. The utility of adoption is not observed, but the decision of the ith household to adopt different categories of CSAT and attain diverse food security levels can be shown as:

$$F_{jit} = \begin{cases} 1 \quad if \ -\infty < F^*_{jit} < c_{t1} \\ 2 \quad if \ c_{t1} \leq F^*_{jit} < c_{t2} \\ \ldots \\ J \quad if \ c_{tJ} \leq F^*_{jit} < \infty \end{cases} \tag{3}$$

The F^*_{jit} is the food security status (latent outcome), c_{tJ} denotes different thresholds or cut points parameters that signify the margins of moving through various CSAT adoption and food security categories. The conditional probability of adopting CSAT is give as;

$$\Pr\,(t_i = \omega_h | z_{ti}) = \Phi^*_1(c_{ti(h-1),}\ c_{tih,}1) \tag{4}$$

where $\Phi(.)$ denotes the standard normal distribution. For h = 0, 1, . . . , H , the conditional probabilities for outcome (food security) category ω_j at treatment (CSAT adoption) category ω_h are specified as;

$$\Pr\left(F_i = 1 \middle| x_i,\ z_{ti},\ t_i = \ \omega_j\right) = \frac{\Phi^*_2\left([c_{1ij}\ \ c_{ti(j-1)}],\ [\infty\ c_{tij}],\ \ \Sigma\right)}{\Phi^*_1(c_{ti(h-1),}\ c_{tih,}1)} \tag{5}$$

Finally, the average treatment effect on the treated (ATT) for food in(security) categories is expressed as;

$$\text{ATT}= E(F_{Ji} - \ F_{0i} | t_i = \omega_h) \tag{6}$$

[3] The Instrumental variables used as an identification are discussed in next sub-section (METE model).

where ji is the food security (HFIAS and HFCS) categories of the ith farm household with respect to the treatment components ($t_i = \omega_h$ i.e. CSAT adoption), h denotes the treatment category (CSAT 1, 2, and 3) of the treated potential outcome, 0 is the potential outcome of CSAT non-adopters (control) treatment level.

3.1.2.2 Multinomial endogenous treatment effect

The continuous food security outcomes, which include the HFIAS score, HFCS and other secondary outcomes, are estimated using the multinomial endogenous treatment effect (METE) model. The METE model is utilized for this analysis due to it's capability to address the issue of endogeneity that might arise as a result of CSAT adoption in this study. Moreover, the METE is suitable for estimating multiple treatment and outcome variables. Following Deb and Trivedi (2006), the METE model is specified as;

$$\Pr\left(\mathrm{t}_{ij} \middle| \mathcal{Z}_i, k_{ij}\right) = \mathbf{g}\left(\mathcal{Z}_i'\varpi_1 + \alpha_1 k_{i1},\ \mathcal{Z}_i'\varpi_2 + \alpha_2 k_{i2} \ldots\ldots\ldots, \mathcal{Z}_i'\varpi_J + \alpha_j k_{ij}\right) \quad (7)$$

$$E\left(\mathrm{F}_i \middle| \mathrm{t}_i, X_i, k_{ij}\right) = X_i'\beta + \textstyle\sum_{j=1}^{J} \delta_j t_{ij} + \sum_{j=1}^{J} \lambda_j k_{iJ} \quad (8)$$

Equation (7) is the multinomial choice of CSAT adoption while equation (8) is the ATT of the food security outcomes. Subscript ij denotes the ith farm household and CSAT categories. j takes the value of 0,1,2 and 3 for non-adopters, adopters of one, two and all three CSAT component respectively. $\mathcal{Z}_i$ represents sets of exogenous variables and k_{ij} denotes unobserved factors. $\mathbf{g}$ assumes a mixed multinomial logit structure of the METE model. The F_i in equation (8) is the outcome variable for food security. X_i is the same with $\mathcal{Z}_i$ in equation (1) with the exclusion of two variables (crop disease and drought shocks) in equation (1) that were used as instrumental variables (IV)[4]. α and β are parameter vector estimates; λ_j represents the effects of CSAT adoption (treatment) relative to non-adoption (control).

[4] Crop disease and drought shocks within the last three years are used as an IV because these variables can influence the CSAT adoption in the survey year but may not affect farmers' food security status in the survey year. Following Di falco and Veronesi (2013), we conducted an IV test. The results indicated that the IVs are not significant in the outcome equation, suggesting the validity of the IVs.

4 Results and discussion

4.1.1 Description of variables used in the analysis.

The variables used in the analysis are shown in Tables 1, Figures 2 and 3. The main outcome variables used are in two folds; continuous (Table 1) and categorical/ordered (Figure 2). As presented in Table 1, the average HFIAS score for the pooled, Mali and Niger are 3.05, 0.327 and 7.044, respectively. Meanwhile, the average HFCS for the pooled, Mali and Niger are 52.15, 64.17 and 34.54, respectively.

We explore other secondary outcomes in this study to provide a potential pathway mechanism through which farm household food security is observed. The outcomes are derived from the share of food consumption from farmers' own crop production and food expenditure share of crop revenue. We disaggregate the share of food consumption into three parts (low, average and high availability) to observe the farm household food security per the level of availability of the food/crop produce. As shown in Table 1 from the pooled sample, the share of household food consumption from farmer's crop output is about 1.5%, 1.9% and 2.3% during low, average and high availability of crop produce. Moreover, the average crop revenue and share of revenue utilized for food expenditure are 227.54 (000' FCFA) and 57.74%, respectively.

Table 1. Summary statistics of variables used for the analysis

Variable	Description	Pooled sample	Mali	Niger	Expected Signs
Main food (in)security outcome					
HFIAS score	Household food insecurity asses scale score (count/continuous)	3.051	0.327	7.044	-
HFCS	Household food consumption scores (count)	52.15	64.17	34.54	+
HFCS Category	Average of three HFCS categories	1.444	1.210	1.787	+/-
HFIAS Category	Average of four HFIAS categories	1.808	1.131	2.800	+/-
Other food (in)security outcome					
Low_Share_HFC	Share of household food consumption from own production during low availability (proportion)	0.015	0.019	0.009	+
Average_Share_HFC	Share of household food consumption from own production during average availability (proportion)	0.019	0.021	0.015	+
High_Share_HFC	Share of household food consumption from own production during high availability (proportion)	0.023	0.023	0.023	+
Crop revenue	Revenue from crop production ('000 FCFA)	227.54	246.87	199.20	+
Shr_Food cons_exp	Share of food expenditure from crop revenue (%)	57.74	54.23	62.89	+
Sociodemographic characteristics					
Household head gender	1 if farmer is male, 0 other wise	0.93	0.99	0.83	+
Household head age	Age of the household head in years	53.45	56.34	49.22	+/-

Household Size	Number of household members	8.91	7.49	10.99	+/-
Education	Formal education years of farmer	2.25	2.34	2.11	+
farmExp yrs	Years of farming experience	33.40	38.24	26.32	+/-
dstnceFrmRsd	Distance from residence to farm in minutes	39.63	34.19	47.61	-
dstnceNrstmkt	Distance to nearest market in minutes	13.67	16.95	8.86	-
Totval hhst	Total value of household asset ('000 FCFA)	1738.78	2485.60	643.97	+
Tot prod asset	Total value of farm productive asset ('000 FCFA)	738.08	1071.77	248.88	+
TTLU	Number of total tropical livestock units owned	11.89	15.56	6.51	+
INC Off farm	Income generated from non-farm activities ('000 FCFA)	64.63	66.48	61.93	+
FarmPlot characteristics					
Farm size	Total farm size area (Ha)	6.47	7.28	5.29	+
Plot number	Number of plots cultivated	1.99	1.81	2.24	
Crop number	Number of crops cultivated	1.57	1.72	1.34	
good soil fertility	1 if soil fertility condition is good, 0 therwise	0.40	0.37	0.44	+
poor soil fertility	1 if soil fertility condition is poor, 0 therwise	0.15	0.11	0.21	-
med soil fertility	1 if soil fertility condition is fair, 0 therwise	0.60	0.52	0.73	+
flat slope	1 if the land topography is flat/normal, 0 therwise	0.62	0.57	0.70	+
Medium slope	1 if the land topography is fair, 0 therwise	0.44	0.38	0.54	+
steep slope	1 if the land topography is steepy, 0 therwise	0.08	0.04	0.12	-
TLB	Total number of labour employed (man/days)	67.73	82.29	46.38	+
Institutional factors					
FBO	1 if the farmer is a member of farmer-based organization, 0 otherwise	0.59	0.82	0.27	+
Credit access	1 if the farmer has access to both formal and informal credit, 0 otherwise	0.11	0.17	0.01	+
conctExtAgnt	1 if the farmer has access to extension, 0 otherwise	0.59	0.73	0.38	+
Location					
R_Sikasso	Farmer who lives in Sikasso region of Mali (dummy)	0.157	0.264	0.441	+/-
R_Segou	Farmer who lives in Segou region of Mali	0.131	0.221	0.415	+/-
R_Koulikoro	Farmer who lives in Koulikoro region of Mali	0.153	0.257	0.437	+/-
R_Kayes	Farmer who lives in Kayes region of Mali	0.153	0.257	0.437	+/-
R_Maradi	Farmer who lives in Maradi region of Niger	0.120	0.296	0.457	+/-
R_Tillaberi	Farmer who lives in Tillaberi region of Niger	0.125	0.309	0.462	+/-
R_Dosso	Farmer who lives in Dosso region of Niger	0.100	0.247	0.431	+/-
R_Zinder	Farmer who lives in Zinder region of Niger	0.0602	0.149	0.356	+/-
Climate_Specific_factors					
Shock _crop_disease	1 if the farmer has experienced crop disease infestation in the last three years, 0 otherwise	0.34	0.191	0.56	+/-
Shock _drought	1 if the farmer has experienced drought in the last three years, 0 otherwise	0.523	0.546	0.489	+/-
N		3371	2004	1367	

The different levels of food security status of farm households in the study area are presented in Figures 2 and 3. As shown in Figure 2 for the HFIAS category indicator, about 62.3%, 9.88%, 12.55 %, and 15.28% of the pooled sample are food secure, mildly food insecure, moderately food insecure and severely food insecure. In Mali, approximately

92.61%, 3.69%, 1.65% and 2.05% of the farm households are food secure, mildly food insecure, moderately food insecure and severely food insecure. However, the farm households in Niger are about 17.85%, 18.95, 29% and 34.67% food secure, mildly food insecure, moderately food insecure and severely food insecure.

Figure 3 presents the HFCS category measurement of food security among the sampled respondents. The pooled sample statistics show that 68.53%, 18.54% and 12.93% of the farm households are of acceptable, borderline and poor food consumption levels. Furthermore, Malian farm households are about 84.48%, 10.03%, and 5% belong to the acceptable, borderline and poor food consumption HFCS category. In Niger, the proportion of farm households in the acceptable, borderline and poor food consumption categories is 45.14%, 31.02% and 23.85%, respectively. Comparing the food security status of the two Sahelian countries considered in this study, the descriptive analysis indicated that farm households in Mali are more food secure than those in Niger.

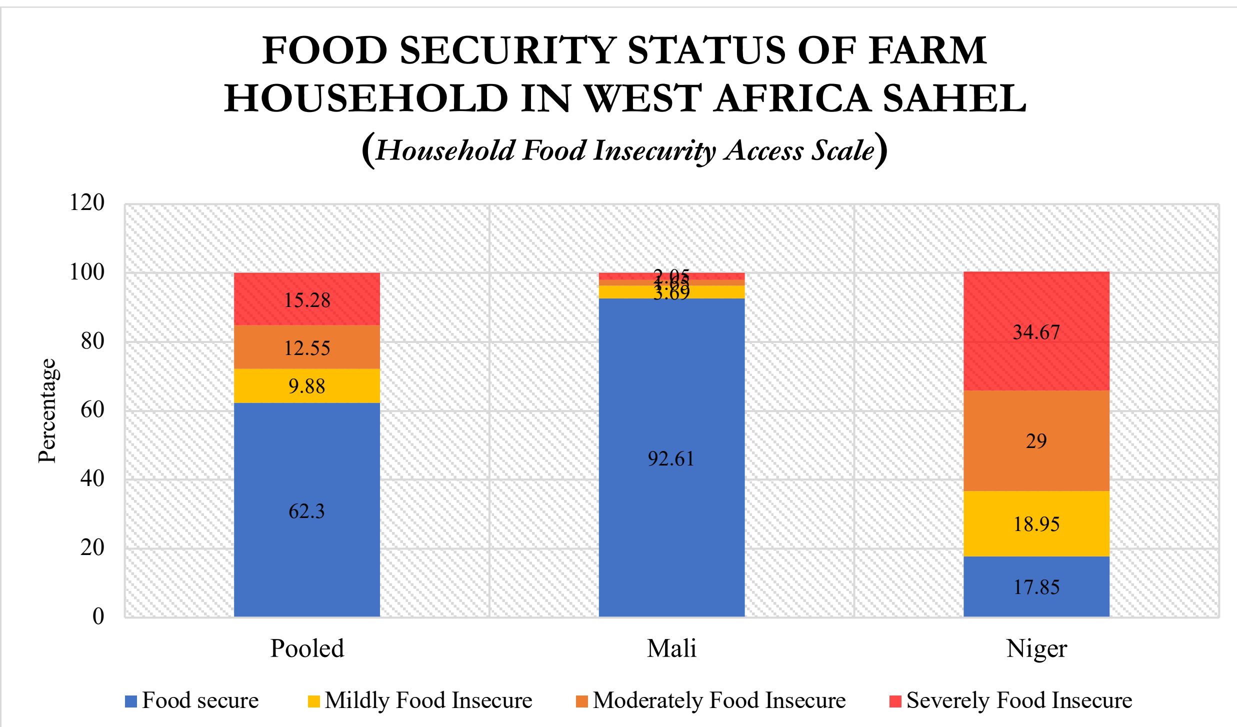

Figure 2. Categories of Household Food Insecurity Access Scale (HFIAS) of the sampled respondents

Source: Authors'

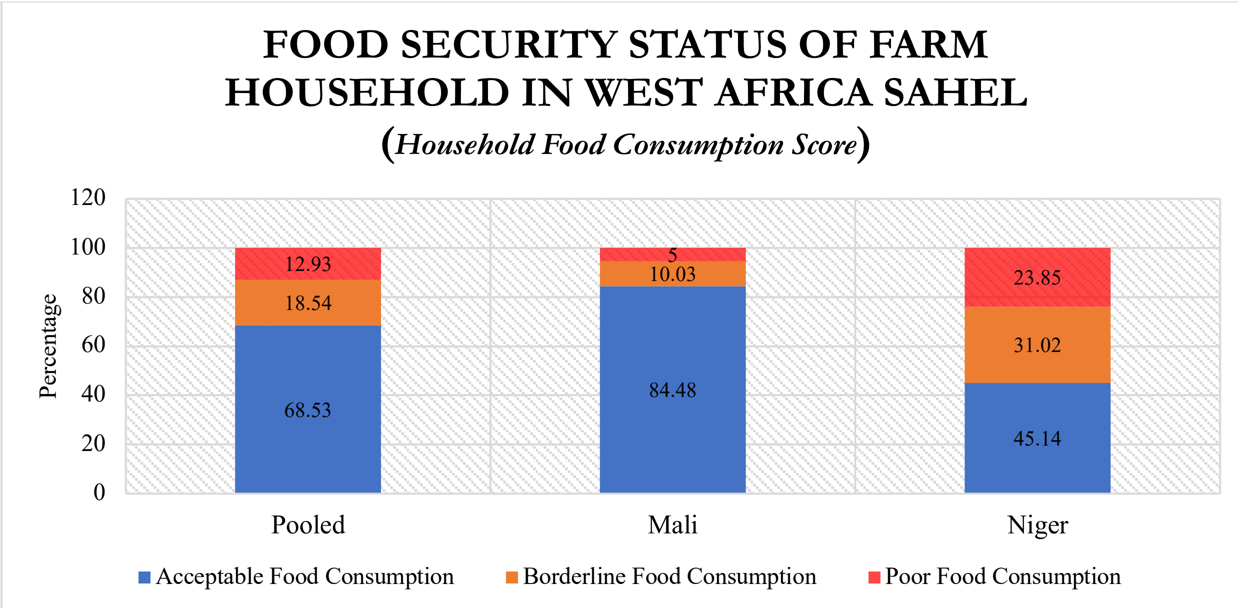

Figure 3. Categories of Household Food Consumption Score (HFCS) of the sampled respondents

Source: Authors'

4.1.2 Drivers of CSAT adoption and household food (in)security

The extended-ordered regression estimates of factors driving CSAT adoption (column two) and food insecurity (columns three to six) among the sampled farmers (both CSAT adopters and non-adopters) are shown in Table 2. We controlled for the regional variations in each country to provide a pooled estimate of the robust effect of CSAT adoption in WASR (both Mali and Niger considered). The bottom part of the Table 2 shows the sensitivity test results of the threshold parameters (cut points) and the correlation between CSAT adoption levels and different HFIAS[5] categories. The results show a negative and significant effect for all three cut points at different levels of CSAT adoption (i.e. from non-adoption to adopting any three CSAT components). This implies that moving across different levels of CSAT adoption could reduce the household food insecurity of the sampled farmers. In addition, the correlation between CSAT adoption and HFIAS is negative and significant. This also affirms that CSAT adoption is likely to reduce household food insecurity among the sampled farmers if not controlled for. Thus, the EOP systematically controlled for potential estimate bias that could occur in this study.

[5] The drivers of HFIAS and HFCS are similar. Thus, to avoid repetition we discussed the results of HFIAS alone. The HFCS results are not shown due to the words limitation of the conference paper. All results can be provided upon request.

4.1.2.1 Drivers of CSAT adoption

The EOP first stage results from Table 2, column 2 reveal that the factors that positively and significantly influence CSAT adoption are education, household and productive assets, total labour, off-farm income, soil fertility and topography, FBO, access to credit and extension agents, and crop disease shock.

Most of the sampled farmers are characterized by low levels of education, which is the situation across many SSA counties (Bello et al., 2021; Danso-Abbeam et al., 2022). However, those who are educated could be more exposed to trending information on climate change and agricultural technologies/practices than non-educated farmers. Thereby increasing their likelihood of adopting CSAT more than their counterparts. Our finding is in tandem with Tabe-Ojong et al. (2023). The adoption of CSAT requires a level of financial commitment in the purchase of inputs and for farm preparations. Thus, farmers with off-farm income, credit access and more household assets could have proportional benefits (access to funds) in adopting CSAT than farmers who are less privileged. Within this background, farmers who have farm plots with better soil fertility and topography are more likely to spend less on farm inputs than those with bad soil fertility and topography, which invariably could enhance their likelihood of adopting CSAT. The positive and statistical significance of FBO and access to extension service variables reiterates the positive role of institutional factors in agricultural technology adoption. Farmers obtain relevant information on agricultural development through channels such as FBOs and extension services, which could aid their probability of adopting CSAT. This finding supports that of previous studies (Abdulai & Huffman, 2014; Baiyegunhi et al., 2022; Khonje et al., 2018; Martey et al., 2021) that showcase the positive significant role of institutional factors on agricultural technology adoption.A plausible reason for the positive relationship between crop disease shock and CSAT adoption is that farmers who have experienced crop loss due to disease infestation in previous farming seasons tend to find appropriate measures to prevent future loss.

On the other hand, farmers' ages, farming experience, farm distance to the residence and drought shock negatively affect the adoption of CSAT. The negative significance of farmers' age and farming experience on CSAT adoption implies that aged and more experienced farmers are less likely to adopt CSAT. This could be because older and more experienced farmers are more accustomed to the traditional farming system and may be more reluctant to try new farming methods than younger and less experienced farmers. This finding is similar to that of Wordofa et al. (2021). The negative association between drought shock and CSAT adoption implies that farmers who are exposed to drought within the last three cropping years are more reluctant to adopt CSAT, which could primarily be due to the high level of risk aversiveness among these categories of farmers. This result corroborates that of Lu et al. (2021) for agricultural technology adoption among farmers in Ghana.

4.1.2.2 Drivers of Household food (in)security

The estimated results (EOP second stage) from columns three to six, Table 2, show various factors driving the food (in)security status of the farmers ranging from non-adopters of CSAT to farmers adopting any three CSAT components. The positive coefficients indicate a likelihood of increased food insecurity, while negative coefficients signal a probability of reduced food insecurity among the farm households.

As shown in Table 2, the majority of the variables (education, household and productive assets, total livestock unit, farm size, off-farm income, soil fertility and topography, extension service contact and location variables) have a negative and statistically significant influence on food insecurity, while household size and a location variable have a positive effect. The positive significant effect of household size on food insecurity implies that the larger the farm household size, the more they are likely to be food insecure. Rural areas in WASR are characterized by large farm households, which could serve as an avenue for facilitating farm operations. However, the larger the farm household, the more the consumption needs (expenditure). Thus, if the number of farm household members doesn't transform into an adequate workforce in the household, there might be a burden on the available resources (including food accessibility) to cater for the household. This outcome corresponds to that of Danso-Abbeam et al. (2022), who found out that farm households with large members tend to be more food insecure in Northern Ghana.

An additional year of farmers' education was found to reduce the probability of food insecurity among adopters of CSAT categories one and two. A plausible explanation is that farmers who are more educated might be well informed about the importance of food nutrition and security and have a diversified source of income (other non-farm jobs) than farmers with less or no education. Resource endowment can be a pathway for improving farm household welfare, which transforms into household food security. This assertion is upheld in our study, as the more the farmers are resourceful (household and productive assets, total livestock unit and farm size), the less likely they are to be food insecure. Similarly, off-farm income reduces the probability of being food insecure among CSAT adopters (two and three). This is because these categories of farmers have a diversified source of income, which can enhance their purchasing power in acquiring food products other than their own farm produce or income obtained from crop production. This result is in tandem with Issahaku & Abdulai (2020). Good and medium soil fertility decreases the propensity of CSAT adopters to be food insecure. Appropriate soil fertility with good farm management practices could result in a bumper harvest, which has a significant implication on the food security status of the farm households.

Furthermore, access to extension agents reduces the likelihood of being food insecure among the farmers (CSAT adopters and non-adopters). Farmers with access to extension agents enjoy the benefit of information about farm operations, which helps farmers in both the production and sales of their crops. Contrary to this finding Danso-Abbeam et al. (2021) found no significant association between food insecurity categories and extension service access among sweet potato farmers in Rwanda. All location variables were found to have a negative correlation with food insecurity, with the exception of two regions (Kayes and Tillaberi) in Niger.

Table 2. Estimates of CSAT adoption and food security drivers

	CSAT	**Food security (Household food insecurity access scale)**			
Variables	**Adoption**	**Non-adopters**	**CSAT 1**	**CSAT 2**	**CSAT 3**
lnHHSzc	-0.18***	0.078	0.21***	0.18***	0.25**
	(0.037)	(0.11)	(0.065)	(0.067)	(0.10)
lnHHage	0.0074	-0.043	-0.062	0.18	0.39*
	(0.080)	(0.22)	(0.15)	(0.13)	(0.21)
lnEdu_yrs	0.087***	0.056	-0.066*	-0.11***	-0.050
	(0.021)	(0.077)	(0.040)	(0.033)	(0.056)
lnfm_exp	-0.045	-0.032	0.046	0.017	-0.062
	(0.035)	(0.097)	(0.062)	(0.055)	(0.096)
lndst_Mkt	-0.00075	0.060	-0.038	-0.0092	0.011
	(0.015)	(0.043)	(0.030)	(0.024)	(0.040)
lndst_rsd	0.00091	0.051	0.065*	0.0033	0.051
	(0.019)	(0.063)	(0.036)	(0.030)	(0.051)
lnHH_ast	0.038***	-0.066***	-0.044**	-0.072***	-0.045
	(0.0096)	(0.023)	(0.018)	(0.021)	(0.039)
lnPrd_ast	0.051***	-0.040	-0.057***	-0.062***	-0.11***
	(0.013)	(0.037)	(0.019)	(0.023)	(0.039)
lnTTLU	0.031	-0.098*	-0.043	-0.056	-0.21***
	(0.022)	(0.056)	(0.038)	(0.036)	(0.066)
lnFm_Sz	-0.053	-0.19*	-0.21***	-0.23***	-0.12
	(0.037)	(0.100)	(0.073)	(0.069)	(0.098)
lnTLB	0.24***	-0.22**	-0.16***	-0.16***	-0.17*
	(0.032)	(0.10)	(0.058)	(0.054)	(0.10)
lnoff_inc	0.0091**	0.011	-0.0072	-0.016***	-0.017*
	(0.0037)	(0.012)	(0.0068)	(0.0058)	(0.010)

good_soilfert	0.19***	-0.12	-0.23**	-0.29***	-0.20*
	(0.049)	(0.17)	(0.091)	(0.073)	(0.11)
med_soilfert	0.026	0.054	-0.18**	-0.13	-0.24*
	(0.051)	(0.16)	(0.090)	(0.083)	(0.14)
flat_slope	0.100*	-0.028	-0.20**	0.0048	0.11
	(0.055)	(0.17)	(0.087)	(0.082)	(0.14)
med_slope	0.011	-0.25	0.023	0.13	0.15
	(0.050)	(0.17)	(0.080)	(0.079)	(0.11)
FBO	0.27***	-0.0077	-0.00035	-0.021	-0.13
	(0.047)	(0.14)	(0.084)	(0.083)	(0.12)
accesCrdt	0.16***	-0.11	-0.072	-0.074	0.044
	(0.045)	(0.14)	(0.075)	(0.073)	(0.12)
conctExtAgnt	0.37***	-0.29**	-0.34***	-0.35***	-0.36***
	(0.045)	(0.13)	(0.074)	(0.069)	(0.11)
R_sikasso	-0.25**	-0.90***	-1.33***	-0.95***	-0.71**
	(0.10)	(0.30)	(0.21)	(0.22)	(0.30)
R_segou	-0.20*	-5.70***	-1.92***	-1.28***	-1.06***
	(0.11)	(0.34)	(0.37)	(0.24)	(0.33)
R_koulikoro	-0.14	-1.17***	-0.96***	-1.20***	-0.44
	(0.11)	(0.37)	(0.20)	(0.23)	(0.27)
R_kayes	-1.75***	-0.48*	-0.19	0.59***	-3.73***
	(0.11)	(0.28)	(0.26)	(0.22)	(0.56)
R_maradi	0.76***	0.44	0.025	0.015	0.27
	(0.095)	(0.35)	(0.15)	(0.16)	(0.25)
R_tillaberi	0.33***	0.29	0.38**	0.30*	0.78***
	(0.095)	(0.26)	(0.15)	(0.16)	(0.25)
R_dosso	0.22**	-0.35	-0.33***	-0.27**	0.11
	(0.093)	(0.26)	(0.12)	(0.13)	(0.25)
SHOCK_CROP_DISEASE	0.20***				
	(0.053)				
SHOCK_DROUGHT	-0.012				
	(0.065)				
HFIAS CATEGORIES					
CSATs#c.cut1		-1.68*	-2.22***	-2.77***	-2.75***
		(1.02)	(0.60)	(0.53)	(0.95)
CSATs#c.cut2		-1.33	-1.87***	-2.23***	-2.17**
		(1.02)	(0.60)	(0.54)	(0.96)
CSATs#c.cut3		-0.95	-1.27**	-1.64***	-1.47
		(1.01)	(0.60)	(0.55)	(0.97)
corr(e.CSATs, e.HFIAS)		-0.74***			
		(0.062)			

Note: CSAT1, 2, 3 denotes adoption of any one, two and all three CSAT component. Robust standard errors clustered at the village level are in parenthesis. *** p<0.01, ** p<0.05, * p<0.1

4.1.3 Impact of food (in)security (categorical outcome)-EOP

As discussed previously, the EOP controls for the endogeneity that could lead to a biased estimate of the food security impact due to CSAT adoption. Table 3 shows the average treatment effect of food (in)security (HFIAS and HFCS) impact of CSAT adoption categories. The estimated results for the CSAT categories (1,2,3) are compared with non-adopters. Table 3, column two to five reveal the four HFIAS categories' results. This study is one of the recent and unique research that disentangles HFIAS with respect to technology adoption, unlike previous studies (Issahaku & Abdulai, 2020; Zakari et al., 2022) that focus on the continuous outcome of HFIAS.

Column two of Table 3 indicates that all CSAT adoption categories (i.e. from one to all three) exhibit a negative and significant relationship with the food secure category. This implies that CSAT adopters are less food secure than non-adopters. Similarly, CSAT adoption (all categories) has a positive and significant effect on moderate and severe food insecurity. Moreover, a positive and significant association was found between adopters of two and three CSAT and mild food insecurity. The positive impact of CSAT adoption combinations on mild, moderate and severe food insecurity implies that adopters of CSAT are more food insecure than non-adopters. These results are surprising and unexpected as CSAT adoption is expected to increase farmers' crop yield/output, which could enhance farm household food security. This result is contrary to many empirical studies (Issahaku & Abdulai, 2020; Maren Radeny et al., 2022; Tabe-Ojong et al., 2023; Zakari et al., 2022) in sub-SaharanAfrica that found a positive effect of agricultural technology on food security.

Furthermore, the HFCS categories in Table 3, columns 6-8 indicate that there is no statistically significant impact of CSAT adoption on food security categories (i.e., food secure, borderline, and food poor). This result implies that there is no difference in the food security status among CSAT adopters and non-adopters. The diverse approach for computing the HFIAS (subjective approach) and HFCS (objective approach) could be a reason for the results not to be strongly similar.

Table 3. Average treatment effects (ATT) estimates of food (in)security impact of CSAT adoption- EOP

	Household Food Insecurity Access Scale (HFIAS) Category				Household Food Consumption Score (HFCS) Category		
CSAT categories	**Food secure**	**Mildly food insecure**	**Moderately food insecure**	**Severely food insecure**	**Acceptable**	**Border line**	**Food Poor**
CSAT1	-0.182***	0.017	0.069***	0.097***	-0.014	0.027	-0.013
	(0.031)	(0.013)	(0.013)	(0.025)	(0.247)	(0.083)	(0.167)
CSAT2	-0.488***	0.106***	0.114***	0.268***	0.022	0.015	-0.036
	(0.067)	(0.017)	(0.017)	(0.059)	(0.476)	(0.176)	(0.302)
CSAT3	-0.573***	0.064**	0.109***	0.400***	0.005	0.015	-0.019
	(0.074)	(0.027)	(0.023)	(0.081)	(0.711)	(0.253)	(0.460)

Note: CSAT1, 2, 3 denotes adoption of any one, two and all three CSAT component. Robust standard errors clustered at the village level are in parenthesis. *** p<0.01, ** p<0.05, * p<0.1

4.1.4 Robustness Check- Impact of food (in)security (Continuous outcome)-METE

We performed a robustness check using the aggregated food security measurement for both the household food insecurity access scale (HFIAS) and food consumption scores (HFCS). The higher the HFIAS, the higher the food insecurity status of the farm household. Moreover, an increase in HFCS denotes a high food security status of the farm household and vice-versa. Using the multinomial endogenous treatment effect (METE), we estimated the impact of CSAT adoption on aggregated food security measurement. Table 4, rows one and three, shows the HFIAS and HFCS impact of CSAT adoption categories.

Table 4. ATT estimates of food security impact of CSAT adoption -METE

Food security	CSAT 1	CSAT 2	CSAT 3
HFIAS score	0.28	-0.13	0.67***
	(0.54)	(0.31)	(0.25)
HFCS	-4.64**	11.86***	0.532
	(2.13)	(3.19)	(2.62)

Note: CSAT1, 2, 3 denotes adoption of any one, two and all three CSAT component. Robust standard errors clustered at the village level are in parenthesis. *** p<0.01, ** p<0.05, * p<0.1

The results from row one show that there is no statistically significant difference between adopters of any one or two CSAT and non-adopters based on HFIAS score. However, HFIAS score exhibits a significant and positive effect on CSAT 3. This implies that the adopters of all three CSAT components are more food insecure than non-adopters. This result contradicts Zakari et al. (2022), who revealed CSAT adopters are less food insecure than non-adopters in Niger.

Furthermore, HFCS has a significant impact on CSAT one and two but no significant impact on adopters of all three CSAT. The negative and significant impact of one CSAT adoption on HFCS suggests that farmers who adopt one of the CSAT components are less food secure than non-adopters. On the other hand, the significant and positive impact of CSAT two adoption on HFCS indicates that adopters of any two of the CSAT components are more food secure than non-adopters. The results of the aggregated HFCS are mixed among the CSAT categories compared with the disaggregated results in Table 3, which indicate a non-significant relationship between HFCS and all the CSAT categories. However, both results show that in most cases, CSAT adoption has no positive impact on food security in the study area.

Overall, the HFIAS and HFCS results indicate that CSAT adoption, regardless of the combinations, has no/negative significant impact on the food security status of the farmers in the study area. There might be various possible reasons for these surprising and unexpected results. We delve deeper into the potential causes of this upheaval in the next sub-section.

4.1.5 Pathway mechanism analysis of food (in)security impact of CSAT adoption.

To ascertain the possible reasons why CSAT adoption does not impact food security positively, we explored a pathway mechanism through the share of food consumption retained from farmers' crop production. We disentangle the share based on farmers' crop output into three components, namely, low, average, and high availability. Table 5 presents the METE estimates of the impact of CSAT adoption on the share of food consumption from farmers' crop production.

Table 5. ATT estimates for the share of household food consumption from own production impact on CSAT adoption.

CSAT categories	Share_HFC Low availability (proportion)	Share_HFC Average availability (proportion)	Share_HFC High availability (proportion)
CSAT 1	-0.014***	-0.013**	-0.016**
	(0.0047)	(0.0062)	(0.0070)
CSAT 2	-0.017***	-0.018***	-0.023***
	(0.0060)	(0.0060)	(0.0072)
CSAT 3	-0.0075*	-0.0062	-0.0080
	(0.0042)	(0.0047)	(0.0056)

Note: CSAT1 ,2, 3 denotes adoption of any one, two and all three CSAT component. HFC denotes Household Food Consumption. Robust standard errors clustered at the village level are in parenthesis. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The results from TabIe 5 show that CSAT adoption (all categories) has a negative and significant effect on food consumption share, ranging from low to high availability (with the exception of CSAT 3 for average and high availability). These findings suggest that CSAT adoption significantly reduces the share of food consumption retained by farm households from their own production. These results could be the possible pathway leading to food insecurity among CSAT adopters, as confirmed in the previous section.

Intuitively, it's expected that the higher the farmers' crop output, the higher the share they would retain for household consumption. However, the reverse is the case in the scenario of CSAT adopters in this study. Even during bumper harvest/crop output (high availability), adopters of CSAT (one and two) tend to reduce the share of food consumed than non-adopters, which perhaps aids their food insecurity status. A plausible explanation behind these results could be that CSAT adopters sell the majority of their crop produce and retain little for household consumption. As CSAT is known to be financially intensive, farmers might want to sell more of their crop produce to obtain enough funds to invest in CSAT in subsequent production seasons or to recover production costs. This can be affirmed by the negative correlation between high availability and CSAT adoption, meaning CSAT adopters sell off their marketable surplus.

Our explanation of the link between the negative food security impact of CSAT adoption and the share of food consumption is based on food products (cereals and legumes) from farmers' production. However, food security components are widely distributed (different food groups), which includes food products not cultivated by the farmers. Another tentative question would be, "what is the evidence that CSAT adopters sell off the majority of their crop produce and not for other purposes, such as gifts"?

We address these concerns by further analyzing the impact of CSAT adoption on crop revenue and the share of crop revenue utilized for food expenditure. The METE estimates from Table 6 show that CSAT adoption (all categories) significantly and positively increases crop revenue, with adopters of all three CSAT components having the highest revenue (121,394.6 [FCFA/Ha]).

Table 6. ATT estimates of CSAT adoption impact on crop revenue and food expenditure share impact of CSAT adoption- METE

CSAT categories	Crop revenue (FCFA/Ha)	Share_Food expenditure (%)
CSAT 1	43,248.2***	-3.73
	(12133.2)	(3.52)
CSAT 2	100,302.5***	-4.14*
	(11058.3)	(2.48)
CSAT 3	121,394.6***	-29.0***
	(14382.6)	(2.68)

Note: CSAT1,2, 3 denotes adoption of any one, two and all three CSAT component. Robust standard errors clustered at the village level are in parenthesis. *** p<0.01 and * p<0.1

This finding supports our previous assertion on the sale of marketable surplus by CSAT adopters. Furthermore, it can be observed that CSAT adoption (any two and all three) has a negative and significant impact on food expenditure share. However, the adoption of any one of the CSAT components has no significant effect. This result implies that adopters of any two and all three CSAT significantly reduce their household food expenditure by 4% and 29% as compared with non-adopters. A plausible explanation is that CSAT farmers tend to utilize less of their crop revenue on food expenditure but rather spend more on non-food expenditures such as agricultural technologies to improve their subsequent farm output. Thus, CSAT might improve crop revenue but, with an associated cost of production (investment in CSAT), could affect their income, which in turn affects their household food consumption pattern.

The implication of this result suggests that while CSAT adoption is vital in boosting crop production, which transforms into increased crop revenue, farmers tend to neglect their food consumption pattern. Thus, the negative food security impact of CSAT adoption can be inferred from farmers' behaviour in their decision between agricultural investments and household welfare (food consumption).

5 Conclusion

Food security, being a major component of the Sustainable Development Goals (SDGs), remains a salient issue globally, most especially in low and developing countries like the West African Sahel. Although several studies have been conducted on the food security impact of agricultural technology adoption, however, the underlying mechanism remains devoid in the literature.

This study provides a comprehensive analysis of the food security impact of CSAT adoption among smallholder farmers in West Africa Sahel (Mali and Niger). We utilize a cross-sectional baseline data of 3,371 farm households from eight agroecological regions (four in each country) in Mali and Niger. The study employs a robust approach to measuring food security using the most widely accepted measures, which are the Household Food Insecurity Access Scale (HFIAS) and Food Consumption Scores (HFCS). We analyzed these measures using robust econometric methods, which allow for multiple treatment variables and outcomes while controlling for systematic bias that could occur in the analysis due to endogeneity/self-selection. The Extended Ordered Probit (EOP) regression econometric method reveals several socio-demographic, farm-plot and institutional factors driving CSAT adoption and the food security status of the farm households. The results from the EOP show that regardless of the CSAT categories, CSAT adoption has no/negative relationship with food security. Our robustness check analysis of the METE also reveals that, in most cases, CSAT adoption negatively impacts the food security of farm households.

We delve deeper into a pathway mechanism analysis to shed more light on the negative effect of CSAT adoption on food security. The empirical findings indicate that the pathway through which the negative association between CSAT adoption and food security occurs is in two folds. The first is through the share of food consumption retained from the farmer's crop output (harvest). The second is through the share of crop revenue utilized for food expenditure. We show that even though CSAT adoption improves the crop revenue of the farmers, their household food consumption pattern tends to deteriorate, probably due to the associated cost/investment in CSAT.

Therefore, the findings from this study have serious implications for achieving SDGs one and two (poverty reduction and zero hunger) and could serve as a basis for policy recommendations. The key significant drivers of food insecurity include household size, assets, TTLU, off-farm income and extension service access. Strengthening the information system in the study area is vital in enhancing food security in the study area. For example, the enlightenment of household heads on the implications of family size on food security and the necessary approaches to deal with it could improve household food consumption patterns. This could be facilitated by both governmental and non-governmental agencies. Encouraging farmers to diversify into rearing tropical livestock units and engaging in secondary jobs other than farming will provide multiple sources of income for farmers, which is critical in improving their livelihood and food security status.

While CSAT adoption is vital in improving crop yields and revenue, it's important to strike a balance between agricultural investment and the food security of farm households. Thus, promoting the adoption of CSAT should include a sensitization on the importance of quality food nutrition within farm households. Since the extension service is one of the fore-front channels in disseminating information to farm households, we recommend upgrading the extension service in the study area. A public-private partnership of extension services is important to intensify the coverage of extension activities in rural areas. Moreover, the curriculum, technology and information system within the extension service could be upgraded to provide farmers with a comprehensive understanding of the pros and cons of technology adoption such as CSAT. Thus, while enlightening the farmers about the benefits of CSAT, the cost implication should also be emphasized, stressing the need for farmers to maintain adequate and quality food nutrition in the household.

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