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Factors driving Climate-Smart Agriculture adoption: a study of smallholder farmers in Koumpentum, Senegal

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Climate change significantly threatens agriculture and food systems in developing countries, especially in Senegal, where agriculture is vital for livelihoods and economic advancement. A study investigated the factors influencing the adoption of Climate-Smart Agriculture (CSA) innovations among smallholder farmers in Koumpentum, Senegal. Through comprehensive research and multistage random sampling, 270 smallholder farmers were interviewed using structured questionnaires. The results indicated that 56.3% of the farmers have adopted CSA practices. Household size, perceived climate change, and access to climate advisory information positively influenced 70.4% of farmers to adopt crop rotation. Additionally, the farmer's experience (in years) and perception of climate change influenced the adoption of conservation tillage. The study highlights how smallholder-specific characteristics and external influences interact to determine CSA adoption. Moreover, it underscores the need for targeted interventions to promote CSA practices, emphasizing the importance of farmer education, access to climate advisory services, and capacity building. Based on our findings, the policy recommendations include aligning CSA innovations with smallholder preferences and local conditions to enhance adoption rates and strengthen climate resilience in agricultural systems. Policymakers should integrate CSA into Senegalese agricultural policy and develop innovative financing mechanisms to encourage the adoption of adaptation technologies tailored to local contexts to address current and future climate risks.

KEYWORDS

CSA adoption, CSA driving factor, correlated innovation, climate change, barriers

1 Introduction

Imagine a nation where the rhythm of life is dictated by the rains, where the fate of families and the national economy hangs precariously on the consistency of the seasons. This is the reality for Senegal, where agriculture, employing nearly 65% of the population, faces an existential threat from climate change (Dabesa et al., 2022) Unpredictable rainfall, soaring temperatures, and relentless droughts are not just environmental concerns; they are economic saboteurs, jeopardizing livelihoods, destabilizing food security, and demanding urgent action to safeguard Senegal's future. The effects of climate change and unstable weather conditions in the Sahel zone have led to adverse consequences for the agricultural sector and biodiversity (Nantongo et al., 2023). The Sahel region, where much of Senegal's agriculture is concentrated, is particularly vulnerable to climate change impacts, including erratic rainfall patterns, prolonged droughts, and rising temperatures. These environmental stressors threaten agricultural productivity, affecting farmers' livelihoods and exacerbating food insecurity (UNCC, 2013). These challenges are further compounded by soil degradation (desertification, declining organic carbon content, wind and water erosion) and limited access to affordable irrigation, a situation worsened by climate change.

In response to these interconnected challenges, the United Nations Sustainable Development Goals (SDGs) provide a global framework aimed at tackling issues related to food security, climate change, and sustainable development. Climate-Smart Agriculture (CSA) is instrumental in achieving several SDGs, particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action). Climate-Smart Agriculture (CSA) represents an integrated approach to managing landscapes—cropland, livestock, forestry, and fisheries that addresses the interconnected challenges of food security, climate change, and natural resource management. CSA practices aim to achieve three main goals: (1) sustainably increasing agricultural productivity and incomes; (2) adapting and building resilience to climate change; and (3) reducing or removing greenhouse gas emissions, where possible (FAO, 2017). These practices vary depending on the specific context but often include strategies such as crop rotation, cover cropping, crop diversification, agroforestry, improved seed varieties, and conservation tillage, the adoption of which is the focus of this study. By enhancing agricultural productivity and building resilience to climate change, CSA enhances food security and promotes sustainable agricultural practices, thereby contributing to SDG 2. Moreover, CSA also contributes to SDG 13 by implementing practices that mitigate greenhouse gas emissions and enhance adaptation to climate change impacts (FAO, 2019).

In the context of Senegal, where agriculture is a major source of livelihood, the promotion of CSA adoption has implications for SDG 8 (Decent Work and Economic Growth) by improving farmers' incomes and creating opportunities for sustainable economic development. Furthermore, CSA practices can contribute to SDG 15 (Life on Land) by promoting sustainable land management and reducing soil erosion. Recognizing the growing threat of climate change to its agricultural sector, the Senegalese government has prioritized CSA as a key component of its development and adaptation strategies. Building upon the foundation laid by the National Adaptation Plan of Action (NAPA) developed in 2006 (UNDP, 2006), Senegal has articulated its commitment to CSA through the National Adaptation Plan (NAP) and Local Climate Change Adaptation Plan (LCCAP). This commitment is further exemplified by the Climate Smart Agriculture Investment Plan (CSAIP), an initiative aimed at transforming agriculture into a benchmark of resilience and sustainability. The CSAIP, driven by the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA), propels the country towards sustainable resilience and enhanced socio-economic growth (CGIAR, 2024).

Technological innovation plays a crucial role in addressing the challenges facing agriculture in the 21st century, including climate change, food security, and resource scarcity. Studies have shown that adopting improved agricultural technologies can significantly enhance productivity, improve livelihoods, and promote sustainable resource management (Charatsari et al., 2022). Climate-Smart Agriculture (CSA) combines technological advancements and sustainable practices to tackle the interconnected issues of food security, climate adaptation, and mitigation. CSA encompasses a wide range of strategies applied across different agricultural systems, aligning with established frameworks such as agroforestry, conservation agriculture, and sustainable land management (Teklu et al., 2023b).

This study focuses specifically on the adoption of the following CSA practices in the Koumpentum cluster: crop rotation, cover cropping, crop diversification, agroforestry, improved seed varieties, and conservation tillage. These practices were promoted in Koumpentum through a joint initiative by the Institut Sénégalais de Recherches Agricoles (ISRA), the Agence Nationale de Conseil Agricole (ANCA), and the AICCRA project (Accelerating Impacts of CGIAR Climate Research for Africa). This initiative in Thiel, Dagabiram, and Kaffrine clusters, in Senegal involves establishing demonstration plots in several villages, conducting farmer field schools on the use of improved varieties and micro-dosing, and disseminating climate service information through mobile phones and radio. These activities were extended to Koumpentum. We chose to examine these six practices crop rotation, cover cropping, crop diversification, agroforestry, improved seed varieties, and conservation tillage because they represent a range of integrated strategies that can enhance resilience to climate change and improve agricultural productivity in the cluster. While improved seed varieties are included in both the cluster initiatives and our study, we expanded our focus beyond CIS and microdosing to encompass a more holistic view of CSA adoption. This broader perspective is essential for understanding the diverse ways in which farmers are adapting to climate change and for identifying opportunities to support the adoption of a wider range of beneficial practices This study examines the adoption of these Climate-Smart Agriculture practices following this initiative, seeking to understand the factors that influence their uptake and long-term sustainability.

Several factors influence smallholder farmers' ability to adopt CSA practices. These include farmers' characteristics (age, gender, education level), farm-level characteristics (farm size, land fertility, land tenure system), socio-economic factors (labor, credit facilities), institutional factors (extension services, capacity programs, farmers' organizations, access to agricultural training), and access to climate information and agro-advisory services (Aryal et al., 2018; Abegunde et al., 2019, 2020; Akinyi et al., 2022; Diro et al., 2022; Kifle et al., 2022; Negera et al., 2022; Tadesse and Ahmed, 2023; Bekuma et al., 2023; Zeleke et al., 2024; Geda et al., 2024; Gudina and Alemu, 2024). Studies have also estimated the impact and effect of CSA adoption on productivity, finding that CSA practices enhance food security and diet by increasing crop yield and income of smallholder farmers (Jena et al., 2023; Asante et al., 2024; Berhanu et al., 2024).

A study evaluating the impact of weather and climate information utilization on the adoption of climate-smart technologies among smallholder farmers in the Tambacounda and Kolda regions of Senegal, as reported by (Nantongo et al. (2021), shows that the rate of adoption in these regions is still low. This highlights the need for further research to understand the specific challenges faced by farmers in different regions of Senegal, including Koumpentum.

A critical research gap in Climate-Smart Agriculture adoption in Koumpentum lies in the limited understanding of how factors like limited water availability, decreased precipitation and degraded soils influence the adoption of these specific Climate-Smart Agriculture practices. While Climate-Smart Agriculture is promoted to enhance resilience and productivity, there is insufficient evidence on how well these practices align with the location-specific conditions and resource constraints faced by farmers in Koumpentum. Key uncertainties include the economic viability of these practices given the cluster of frequent droughts caused by decreased rainfall, the accessibility of climate information services relevant to water management, and the impact of policy and extension support tailored to the needs of smallholder farmers in this area on adoption rates. Koumpentum is an important area for this study because it is representative of other drought-prone areas in Senegal and is an ongoing focal area for the AICCRA CSA initiative. To address these critical gaps and contribute to the effective implementation of CSA in Koumpentum, this study investigates the following research questions: (a) Which CSA practices do smallholder farmers who grow food crops in the Koumpentum cluster adopt? and (b) what factors influence smallholder farmers to adopt CSA? By identifying the specific barriers and opportunities to CSA adoption in this cluster, this study will provide valuable insights for designing targeted interventions that can effectively promote sustainable agricultural practices and improve food security at the local level, directly contributing to SDG 2. Moreover, by focusing on these climate-resilient agricultural practices, the study will inform strategies for enhancing climate change adaptation in the agricultural sector, thus supporting SDG 13.

2 Materials and methods

2.1 Study area

The study was conducted in the Koumpentum cluster located 13.981 N on the latitude and -14.563 W longitude, a department located in the Tambacouda region in Senegal, southeast of Senegal in the new peanut basin known as the largest region (Figure 1). The Koumpentum department covers an area of 6,312 km² with 199,457 people (ANSD, 2017). With innovative agricultural practices and the dissemination of climate-smart technologies, the AICCRA (Accelerating Impacts of CGIAR Climate Research for Africa) project strategically aims to enhance climate resilience and sustainable agricultural productivity in Koumpentoum. Koumpentoum cluster, a semi-arid area, located in the Sudano-sahelian found in the country's agro-climatic zoning of the Soudanion-Gunian (Joseph et al., 2023). It has a unimodal rainfall pattern; the rainy season lasts from June to October with an average yearly rainfall above 700mm. The area has a mean annual temperature ranging between 43.2 and 45.1 °C with monthly temperatures ranging between 24 °C and 38°C (Joseph et al., 2023). In terms of soil type, the soil of the Koumpentum cluster is Sandy loam, a well-balanced mixture of sand, silt, and clay. The main economic is agriculture. The agricultural sector comprises small-scale commercial and subsistence agriculture for livestock and cropping systems. The agriculture system mainly depends on rain; thus, their production system is climate-dependent and highly susceptible to climate change-related problems that affect the sustainability of agricultural productivity (UNCC, 2013). The major crops grown in the Koumpentum cluster are Sorghum, Pearl Millet, cowpea, and Peanut among many others. As a result, it is critical to appreciate the adoption of Climate-Smart Agriculture and the challenges that smallholder farmers encounter while employing the approaches.

2.2 Household selection and data collection

The selection of the sampling framework was based on the intervention program of the AICCRA(Accelerating Impacts of CGIAR Climate Research for Africa), as well as the sampling design for the selection of survey respondents. The target population for this study consisted of households in the Ndame and Ida Mouride district, located within Koumpentum. These districts were selected because they are communities where the AICCRA project is being implemented. A multi-stage sampling approach was used. In the first stage, both the Ndame and Ida Mouride district were selected for inclusion in the study. In the second stage, 11 villages' each were selected for both district, adding up to 22 villages been sampled. All villages within the two districts were included to ensure comprehensive coverage of the project area. In the third stage, 10 households within each village were randomly selected, however oversampling of additional 50 households were added to the sampling population resulting in a total sample size of

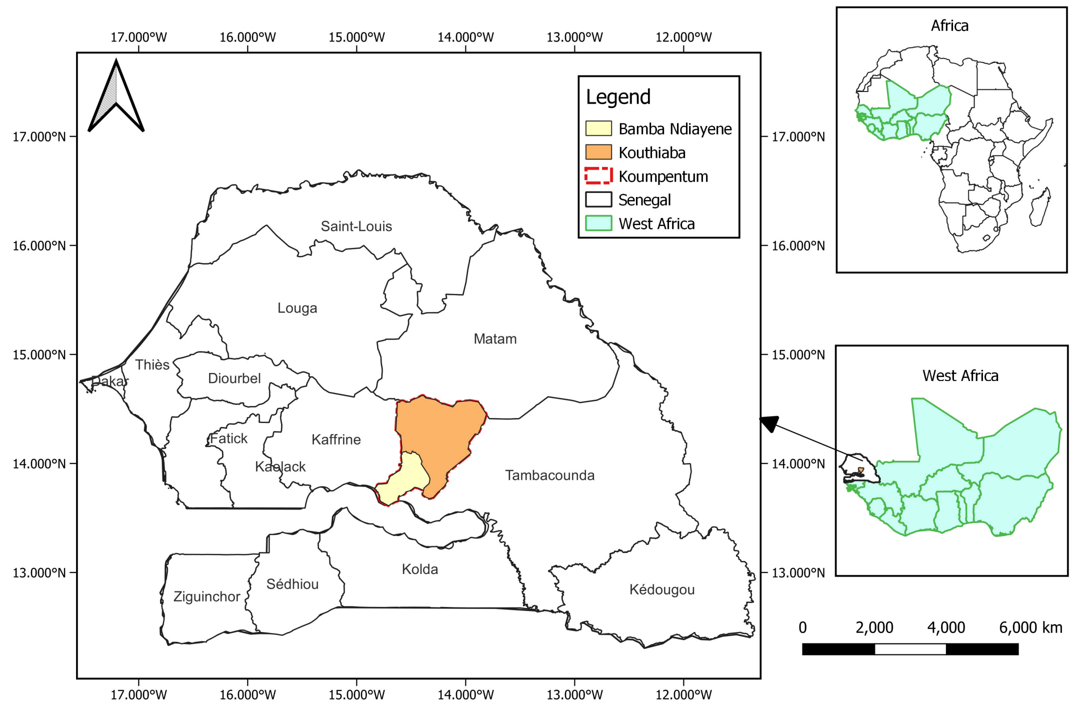

FIGURE 1
Study map area of Koumpentum cluster.

270 households. The oversampling was done to reduce error margin.

The study data were collected from a cross-sectional household survey of farmers who raised crops and livestock in the Koumpentum during the post-harvest season of 2023. In this study, a household was defined as a person or group of persons who live together in the same house or compound, share the same housekeeping arrangements, and are catered for as one unit, meaning they commonly provide and share food (Stewart et al., 2015). The household head, either male or female is regarded as the decision maker on land use and approves to access the target respondents and administration of the survey. Respondents were either household heads or adult household members well acquainted with household activities who were interviewed at the household level. The study used questionnaire to gather data from 270 smallholder farmers. The data was collected in the field using the Kobo-collect digital data collection tool, a mobile platform for researchers and professionals working in offline and online environments. This tool offers user-friendly, secure, and scalable capabilities. A team of well-trained enumerators and supervisors collected data in the villages and commune of the Koumpentum cluster. The survey collected information on household characteristics such as age group, gender, educational level, gender, year of experience, farm size, land ownership, perception of climate change, access to climate information(iSAT tool provides climate advisory information on current and forecasted weather data, advisory services messages which help farmers manage climate risk through tailored farming recommendation etc via farmers mobile phone, disseminated by a private organization called Jokolante translated in the local language for better understanding) and various Climate-Smart Agriculture practices adopted by smallholder farmers.

Ethical approval for this research was obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), under the approval number IECICRISAT/30082022/06. Before the data collection, an informed consent process involved reading a consent form to each respondent providing detailed information. The consent form included the objectives of the study, emphasizing the voluntary nature of participation, and affirmed the right of respondents to withdraw from the study at any time. Additionally, it outlined the measures implemented to ensure the confidentiality and anonymity of the collected data. Throughout the analysis, all data underwent anonymization processes and were stored securely.

2.3 Measurement of adoption and CSA

Agricultural technology adoption theory is a broad, multi-disciplinary field drawing on elements of decision theory (specifically, the Adopter Perception and Economic paradigms) and diffusion of innovations theory (the Innovation Diffusion paradigm). These theories attempt to explain why some farmers adopt new technologies while others do not, a topic that has been extensively studied, including in the context of Climate-Smart Agriculture (CSA) (Ruzzante and Bilton, 2021) (Equations 1, 2). These studies often estimate a function, typically using correlational techniques, to explain adoption behavior as a function of variables collected through farmer surveys. This approach generally assumes that farmers are rational actors who aim to maximize an unobserved expected utility function. CSA aims to achieve sustainable and productive agricultural practices that enhance food security and environmental sustainability in the face of climate change and variability. Recognizing the importance of incorporating local knowledge and priorities, a workshop was organized by the AICCRA project before the cropping season in the Koumpentum cluster. Lead farmers and farmer representatives, selected by their peers, participated in this workshop. It served as a platform for farmers to articulate their specific challenges related to climate change and soil degradation, as well as to share their insights on potential solutions. This initial workshop informed the development of the survey instrument designed to assess the agricultural practices employed by farmers in the region. The survey was administered at the end of the cropping season. Based on farmers responses to the survey, we identified six prominent CSA practices being implemented. These were the six most frequently reported practices, representing those adopted by respondents: crop rotation, cover cropping, crop diversification, agroforestry, improved seed varieties, and conservation tillage. While other CSA practices were mentioned by farmers, such as water harvesting and management, these were reported by fewer respondents and were therefore not included in the present analysis. This focus on the most prevalent practices allowed us to concentrate on strategies with the greatest observed adoption in the cluster. These six practices align with recommended CSA strategies for the cluster, addressing key challenges such as soil degradation, water scarcity, and climate variability (FAO, 2017). While farmer perception is crucial, the selection of these practices is also supported by existing research on their effectiveness in similar agroecological contexts (Zagre et al., 2024).

2.4 Descriptive statistics and data analysis

Table 1 summarizes the descriptive statistics of variables input in the model as factors likely to influence the adoption of CSA practices of the smallholder farmers in the study area they were classified as independent variables and Dependent variables (CSA practices). The selection of the independent variables for the logit regression model was based on theoretical, and conceptual frameworks, and past empirical adoption of agricultural technologies (Agidie et al., 2013; Ruzzante and Bilton, 2021). They include socio-demographics such as age, gender, and education level of the household head. Economic factors such as farm size may influence farmers' decisions to adopt agricultural technology. Institutional variables such as access to climate agro advisory are important in enhancing adoption. Climate advisory information on climate change and CSA practice-related topics such as climate change, and agronomic practices also influence the likelihood of the farmers to adopt these technologies (Ntshangase

TABLE 1 Description of variables.

Variable	Type	Description of variable and measurement
Independent Variables		
Age(HH)	Quantitative	Age of Head of Household
Gender	Qualitative	Dummy=1 if the farmer's gender is male, 2=if farmer is female
Educational Level	Qualitative	No education=1, Primary =2, Secondary=3, Tertiary=4, Koranic=5
Year of Experience	Quantitative	The farmer's year of farming experience
Land ownership status	Qualitative	Owner=1, Leased=2, Inherited =3, Don't owned any =4
Farm size	Quantitative	Size of farmland
Household size	Quantitative	Number of members of the household
Perceived Climate change	Qualitative	Dummy=1 if the farmer perceived Climate change and variability, 0=if otherwise
Access to Climate Advisory Information	Qualitative	Dummy=1 if the farmer has access to climate advisory information, 0=if otherwise
Dependent Variables		
Crop Rotation	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise
Cover crops	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise
Crop Diversification	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise
Agroforestry	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise
Improved seed	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise
Conservation tillage	Qualitative	Dummy=1 if the household adopted the practice, 0 otherwise

et al., 2018). The dependent variables are the adoption of Crop rotation(planting different crops in a sequence on the same plot), cover cropping(planting crops primarily for soil cover and improvement), Crop diversification(cultivating multiple crops on the same farm), Agroforestry(integrating trees and shrubs into agricultural systems), Improved seed(using certified seeds of improved crop varieties known for higher yield, pest resistance, and/or drought tolerance, and Conservation tillage(tillage practices that minimize soil disturbance and erosion). A smallholder farmer is considered an adopter if s(he) at least applies one Climate-Smart Agriculture innovation. We captured adoption (Equation 3) as a variable that takes the value of one for adopters and zero otherwise.

Adoptions of CSA practices are correlated (Ruzzante and Bilton, 2021; Negera et al., 2022; Teklu et al., 2023b). The correlation is caused by either technology complementarity or practice substitutability.

$$Adoption = f(X) \tag{1}$$

Adoption= Observed adoption behavior of the farmer and **X**= $\{x_1,x_2 \ldots\ldots x_n\}$ is a matrix of socioeconomic, personality, environmental, farm financial, farm management, or external factors gathered through surveys.

We then assume that adoption is the realized value of an unobserved latent utility function U. U* is the estimate of U, which is most often assumed to be a linear function of X (Marenya and Barrett, 2007):

$$U* = X\beta + \varepsilon \tag{2}$$

Where β is a vector of estimated parameters and ε is a random error term. The i^{th} farmer is assumed to adopt if the expected utility of adopting the innovation is greater than 0:

$$Y_i = \begin{cases} 1, & if \;\; U_i^* \geq 0 \\ 0, & otherwise \end{cases} \ldots \ldots \ldots \tag{3}$$

When many CSA innovations can be adopted and innovations are independent of one another, it is presupposed that the error terms in Equation 2 jointly follow a multivariate normal (MVN) distribution. Assuming the CSA practices are CR (Crop rotation), CC(Cover cropping), CD(Crop diversification), AF(Agroforestry), IS(Improved seed), and CT(Conservational tillage), then (μ CR, μ CC,μ CD, μ AF, μ IS, μ CT) ~ MVP (0, Ω) and the symmetric [6×6] covariance matrix Ω is given:

$$\Omega = \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}$$

The coefficient pairwise correlation of the error terms of any two of the estimated adoption equations of CSA practices in the model represented by p.

Logistic regression analysis was conducted to examine the factors influencing the adoption of CSA innovations among smallholder farmers in the cluster. This involved utilizing logit models to analyze the relationship between a binary dependent variable and a set of independent variables. The reason for the application of the logit model in this study is that the binary response variable depicts the factors affecting the adoption of climate-smart innovations. The logistic model for "k" independent variables (Xi, X2, X3,…, Xk) is represented by Equation 4:

$$Logit\ P(\chi) = \alpha + \sum_{j=1}^{k} \beta_i x_i \tag{4}$$

βi represents the odds ratio for an individual with the characteristics *i* compared to an individual without characteristics. βi refers to the regression coefficient, and α represents a constant (Fosu-Mensah et al., 2012).

3 Results

3.1 Socio-economic characteristics of smallholder farmers

The study reveals significant insights into the characteristics of smallholder farmers households in the AICCRA(Accelerated Impacts of CGIAR Climate Research for Africa) project area, with a focus on demographic, socioeconomic, and gender dynamics (Table 2). Male-headed households dominate at 77.4%, while female-headed households account for 12.2%. However, 10.4% of respondents represented their husbands, highlighting complex gender dynamics within these households. The adoption rate of Climate-Smart Agriculture (CSA) practices stands at 56.3%, with 73.7% of adopters being male. This adoption rate suggests that CSA technologies and practices are being implemented by a significant portion of the farmers sampled. Further research is needed to directly assess the level of awareness of CSA practices among the farmer population.

The demographic profile of smallholder respondent farmers presents both challenges and opportunities. With an average age of 41.8 years and Koranic education as the primary form of schooling, literacy levels among these farmers are low (secondary education 2.2%, primary 3%, higher 0.7%, Koranic 25.11%, no education 62.2%).

The average family size is approximately 10 people, with farmers cultivating an average farm area of 8 hectares. Land ownership is primarily through inheritance (42.2%) or personal ownership (38.9%), and the average agricultural experience is 10 years.

Climate change awareness and its impact on agricultural practices are evident among farmers in the study area. The effects of climate change are manifested in various ways, including crop failures. Access to agricultural advisory information on climate change is available to 62.6% of smallholder farmers, with 63.9% of those with access adopting CSA innovative practices (Figure 2). This correlation between information access and adoption rates underscores the importance of knowledge dissemination in promoting sustainable agricultural practices.

TABLE 2 Socio-economics characteristics of respondents Household (n=270).

Variable		Adopters	Non-Adopters
	Overall (mean or %)	Frequency (%)	Frequency (%)
Age(yrs)	41.7yrs		
21-35		56(36.8)	44(37.3)
36-45		48(31.6)	30(2523.4)
46-Above		48(31.6)	4344(37.3)
Gender			
Male	77.4%	112(73.7)	97(82.2)
Female	22.6%	40(26.3)	21(17.8)
Education			
No Education	62.2%	121(79.6)	65(55.1)
Primary	3%	6(3.9)	2(1.7)
Secondary	2.2%	2(1.3)	4(3.4)
Higher	0.7%	1(0.66)	1(0.85)
Koranic	25.1%	22(14.5)	46(39.0)
Landownership			
Inherited	42.2%	57(37.5)	48(40.7)
Owners	38.9%	25(16.4)	12(10.2)
Leased	13.7%	67(44.1)	47(39.8)
Don't own	5.2%	3(2.0)	11(9.3)
Farm size (ha)	8.3ha		
1_5		126(84.6)	96(89.7)
6_10		14(9.4)	9(8.4)
>11		9(6.0)	2(1.9)
Year of Experience	10.8years		
1_10		106(69.7)	93(78.8)
11_20		21(13.8)	9(7.6)
>21		25(16.5)	16(13.6)
Household size	9.7		
1_5		50(32.9)	59(50)
6_10		34(22.4)	27(22.9)
>11		68(44.7)	32(27.1)
CSA Adopters		152(56.3)	118(43.7)
Access to CAI	62.60%	108(63.9)	61(36.1)
Perceived CC	100%	152(56.3)	118(43.7)

(Source: Authors' compilation from the survey Data (2023)) CSA, Climate-Smart Agriculture; CAI, Climate Advisory Information; CC, Climate Change.

3.2 Farmers' perceptions of climate change impacts on productivity

Table 3 presents farmers' perception and awareness of observed changes in climate variability over the past years. The majority of respondents (100%) acknowledged experiencing climate changes. Regarding temperature trends, a large majority (94.4%) reported an increase, while only a small fraction (5.6%) noted a decrease. When asked about rainfall, 35.1% indicated a decrease, 26.6% reported an increase, and 38.3% observed both increases and decreases. In terms

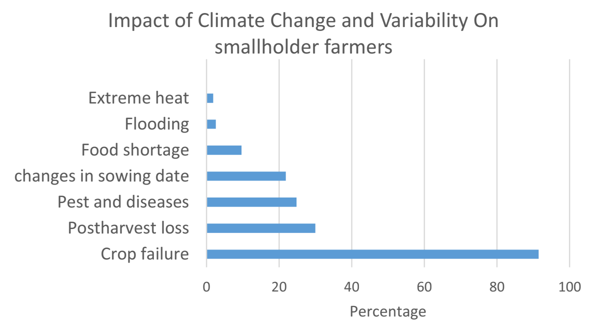

FIGURE 2
Perceived climate change and variability impact on productivity (Source: Authors' compilation from the survey Data (2023)).

TABLE 3 Farmer's awareness of one or more changes in climate variability.

Perception of Climate Change	Total Respondent	%
Yes	270	100%
No		
Temperature trend in the last 30 years		
Change in Temperature	198	
Increased	187	94.4
Decreased	11	5.6
Increased and decreased	62	31.3
Rainfall trend in the last 30 years		
Change in Rainfall	94	
Increased	25	26.6
Decreased	33	35.1
Increased and decreased	36	38.3
Onset/Arrival of Rainfall		
Change in Onset	64	
Increased	26	40.6
Decreased	19	29.7
Increased and decreased	19	29.7
Cessation of Rainfall		
Change in Cessation	27	
Increased	19	70.4
Decreased	8	29.6
Increased and decreased	0	0.0

(Source: Authors' compilation from the survey Data (2023)).Note; Total may not add due to multiple responses by respondent.

of rainfall patterns, 40.6% perceived changes in the onset of rain, and a substantial 70.4% reported changes in the cessation of rainfall.

Figure 2 visually represents the impact of these climate changes and variability on smallholder farmers food security, focusing specifically on the most critical challenges reported by respondents. As shown in Figure 2, crop failure was identified as the most significant impact, with 91.5% of respondents reporting it as a major issue. This aligns with the substantial proportion of respondents in Table 3 who reported experiencing decreased or highly variable rainfall (35.1% and 38.3%, respectively), suggesting a strong connection between water availability and crop production. The graph also highlights postharvest losses (30%) and increased incidence of pests and diseases (24.8%) as other major concerns. These findings can be related to the observed changes in rainfall patterns as shown in Table 3, particularly the delayed or erratic onset of rains, which can create favorable conditions for pest outbreaks and make crops more vulnerable to postharvest losses due to delayed harvests or difficulties in drying. While Figure 2 focuses on the most prominent food security challenges, Table 3 provides a more granular view of how farmers perceive changes in various climate variability indicators, such as the onset and cessation of rainfall, which can contribute to these challenges.

3.3 Climate smart agriculture adopted in the study area

The integration of climate-smart agricultural innovations among farmers has emerged as a pivotal strategy for addressing the challenges posed by climate change while simultaneously enhancing food systems. As shown in Figure 3, there is a variation in the adoption of various Climate-Smart Agricultural (CSA) practices among smallholder farmers within the study area, revealing a preference for certain techniques. Notably, crop rotation manifests as the predominant practice, boasting a significant adoption rate of 70.39%. This pronounced preference suggests farmers recognize the established advantages that crop rotation for soil fertility, pest management, and improved yield, in a changing climate. Following crop rotation, improved seed is the next most adopted at 34.21%. This trend indicates that farmers are also emphasizing practices that not only improve soil health but also harness enhanced genetic resources, which are essential for adapting to environmental conditions. Crop diversification has been embraced by 13.16% of the respondents, highlighting its importance in risk mitigation and resilience, while cover crops were adopted by 14.47% of respondents. The uptake of cover crops may be attributed to various constraints, including limited seed availability, insufficient awareness regarding their specific benefits, and competition with more lucrative cash crops. Conversely, the adoption rates for agroforestry is markedly lower, recorded at 1.97%. The notably low adoption rate of agroforestry is likely correlated with the long-term nature of the investment and the challenges of integrating trees into existing farms. These findings emphasize the need for targeted interventions to encourage broader uptake of CSA practices, tailored to the specific circumstances of farmers in the region.

Despite the adoption of some CSA practices, several barriers impede wider and more effective implementation, as illustrated in Figure 4. Lack of knowledge or information stands out as a major constraint, with 29.6% of respondents identifying it as a challenge.

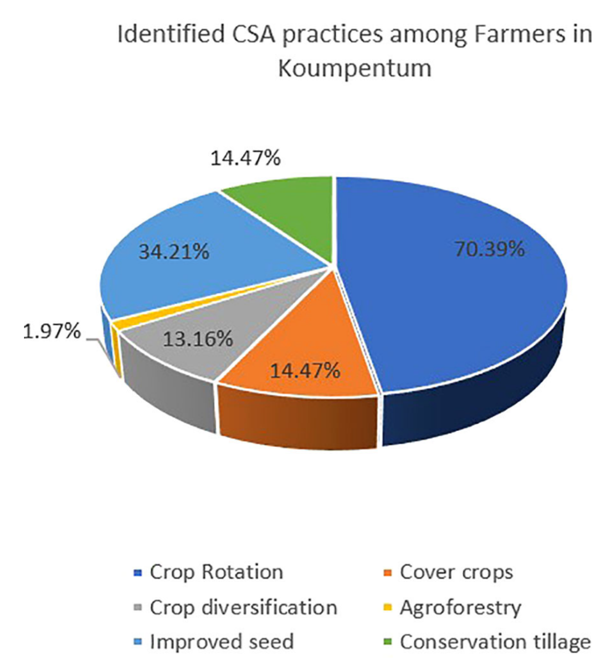

FIGURE 3
CSA innovations among farmers.

This highlights the need for improved extension services and information dissemination strategies. Financial limitations also pose a significant obstacle, with 22.4% of farmers reporting it as a barrier. This suggests that access to credit and affordable financing options is crucial for enabling CSA adoption. Insufficient or lack of resources e.g land, labour, water were also identified by 6.6% of respondents. Furthermore, 3.9% farmers perceive climate variability and change itself as a barrier, potentially due to the increased risks and uncertainties it creates. Unreliable markets (1.97%) can discourage investment in CSA practices if farmers are unsure about market access for their products. Finally, lack of government support (1.32%) underscores the need for policies and programs that incentivize and facilitate CSA adoption. Addressing these interconnected challenges is crucial to enhance the adoption of CSA innovations and improve the livelihoods of farmers in the region.

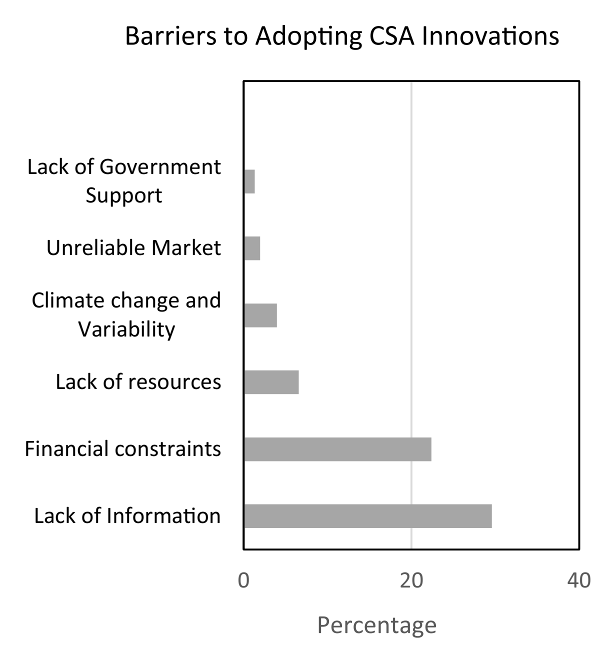

FIGURE 4
Barriers to adopting CSA.

The adoption of CSA technologies and innovations heavily depends on farmers' perceptions and adaptive capacities, as well as the effectiveness of dissemination methods. Given that different CSA practices have varying levels of relevance in mitigating climate change impacts, farmers must be aware of the practices most pertinent to their specific situations. As shown in Table 4, the significant correlations indicate that the adoption of one CSA practice is often associated with the adoption of others. This suggests that farmers who are open to adopting one CSA practice are likely to adopt multiple practices. The strongest correlations are observed between crop rotation and crop diversification (0.47), and between crop rotation and improved seed (0.46), indicating that these practices are often adopted together. Understanding these correlations can help policymakers and extension services design integrated CSA programs that promote multiple practices simultaneously, enhancing overall adoption rates and climate resilience.

3.4 Factors influencing the adoption of climate smart innovation

Table 5 presents the results of the logit regression analysis examining the factors influencing the adoption of various CSA innovations. The included variables collectively explain some of the variation in CSA adoption. However, the influence of individual factors varied across the different CSA practices.

Education emerged as a significant predictor of adoption for several CSA practices, but with a negative association including crop rotation ($\beta = -0.328$, $p < 0.05$), cover cropping ($\beta = -0.168$, $p < 0.05$), crop diversification ($\beta = -0.215$, $p < 0.05$), and improved seed varieties ($\beta = -0.147$, $p < 0.05$), and improved seed varieties ($\beta = -0.147$, $p < 0.05$). The negative coefficients suggest that higher levels of education are associated with lower adoption of these specific practices. This counterintuitive finding warrants further investigation to understand the underlying reasons. More educated farmers may be more likely to adopt different, perhaps more intensive or technologically advanced, agricultural practices not captured in this study. Alternatively, it could suggest a gap in the type of education or training received, which may not be adequately addressing the benefits and implementation of these specific CSA practices. Household size positively influenced the adoption of crop rotation ($\beta = 0.339$, $p < 0.05$) suggesting that larger

TABLE 4 Pairwise correlation of adoption of CSA innovations.

CSA Innovations	Crop Rotation	Cover crops	Crop Diversification	Agroforestry	Improved seed	Conservation Tillage
Crop Rotation	1					
Cover crops	0.32**	1				
Crop Diversification	0.47**	0.298**	1			
Agroforestry	0.31**	0.182**	0.311**	1		
Improved seed	0.46**	0.297**	0.306**	0.104	1	
Conservation Tillage	0.089	0.201**	0.135**	0.239**	0.24**	1

*Correlation Coefficient values, **, significant at 5%.*(Source: Authors' compilation from the survey Data (2023)).

households may have more labor available for these practices. Years of farming experience had a positive and significant effect on the adoption of agroforestry ($\beta = 0.041$, $p < 0.05$) but a negative effect on conservation tillage ($\beta = -0.430$, $p < 0.05$). The positive association with agroforestry may reflect accumulated knowledge and experience with integrating trees into farming systems over time. The negative association with conservation tillage, while unexpected, might indicate that more experienced farmers are less willing to change their established tillage practices.

Furthermore, Access to Climate Advisory Information (CAI) had a positive and significant effect on the adoption of crop rotation ($\beta = 0.550$, $p < 0.05$), likely because CAI, including seasonal rainfall forecasts and drought risk warnings, reduces uncertainty about future weather conditions, enabling farmers to make informed decisions about crop selection and timing, and because CAI services may also educate farmers about the specific benefits of crop rotation and promote its integration with other CSA techniques. Moreover, perceived climate change, particularly changes in rainfall patterns and increased temperatures, had a positive and significant effect on improved seed varieties ($\beta = 1.186$, $p < 0.05$), crop rotation ($\beta = 1.358$, $p < 0.05$), and conservation tillage ($\beta = 1.460$, $p < 0.05$), suggesting that farmers who perceive climate change are more likely to adopt these practices as an adaptation strategy.

4 Discussion

Farmers in the study area perceive climate change as negatively impacting their agricultural production, driving climate change adaptation strategies. Our research indicates that smallholder farmers who perceive climate change as significantly affecting their agricultural output are more likely to implement CSA practices. This finding aligns with studies conducted across Africa. Farmers who have observed the effects of rising temperatures and declining rainfall are more likely to adopt CSA methods like drought-resistant varieties and water conservation techniques to mitigate these impacts. Research has highlighted the role of risk perception in adaptation behavior, particularly in West Africa. Studies suggest that farmers who have directly experienced

TABLE 5 Logit regression showing Factors influencing the Adoption of CSA innovation.

Variables/ CSA Innovations	Crop Rotation	cover cropping	Crop diversification	Agroforestry	Improved seed	Cons. tillage
Age	-0.277	-0.079	0.156	-0.0257	0.174	0.108
Gender	0.095	0.206	0.205	0.0336	0.201	0.097
Education	-0.328**	-0.1683**	-0.2146**	-0.0041	-0.1465**	0.164
Landownership	0.153	-0.108	0.099	-0.0092	-0.05	0.125
Farm size	0.312	-0.012	-0.236	-0.0414	0.324	0.154
Year of experience	-0.007	-0.069	-0.024	0.0407**	-0.03	-0.43**
Household size	0.339**	0.121	0.275	0.0165	-0.107	-0.004
Access to CAI	0.55**	-0.078	0.081	0.0383	0.294	0.363
Perceived CC	1.358**	0.878	0.488	0.0024	1.186**	1.46**
Constant	-1.987***	-1.312	-1.67	0.096	-2.079**	-4.44**

Correlation Coefficient values, **, significant at 5%. Source: Authors' compilation from the survey Data (2023)).

climate-related stressors, including increasing temperatures, erratic rainfall, and crop failure, are more likely to adopt CSA measures (Fosu-Mensah et al., 2012; Abegunde et al., 2020). Recognizing the threats associated with severe weather and changing climate trends, surveyed farmers are likely motivated to seek and implement CSA practices to protect their livelihoods and enhance resilience. This direct experience of climate change impacts likely strengthens farmers' risk perception, motivating them to take proactive steps to adapt their agricultural practices. This underscores the importance of farmer-centered climate change adaptation strategies that build on local knowledge and experiences. Senegalese policies should prioritize raising awareness about climate change and its specific impacts on agriculture in different regions. This can be done through farmer field schools, community radio programs, and collaborations with agricultural extension services. Policies should support research into locally adapted CSA practices.

Building on this understanding of climate change, access to and utilization of climate advisory information (CAI) significantly impact the adoption of CSA practices for climate change adaptation and mitigation. The availability and accessibility of such information are crucial for shaping farmers' knowledge and perceptions of climate change, and their capacity to adopt mitigation strategies (Ado et al., 2019). Our finding that CAI access is particularly significant for crop rotation adoption highlights the direct relevance of climate information to this specific practice. Crop rotation planning requires careful consideration of seasonal weather patterns, including rainfall amounts, timing, and variability. Farmers need reliable forecasts to choose appropriate rotation crops, determine optimal planting times, and manage the rotation cycle effectively. CAI, particularly seasonal forecasts and tailored agro-meteorological advisories, provides precisely this type of information, empowering farmers to make informed, climate-smart decisions about their crop rotations. This aligns with studies emphasizing the importance of timely and relevant information for agricultural decision-making (Aker and Mbiti, 2010; Nantongo et al., 2023). Our results extend this general principle to the specific context of CSA adoption, highlighting the critical role of CAI in facilitating informed decisions about crop rotation. The lack of a significant effect of CAI on other CSA practices may be due to several factors, including the possibility that these practices are adopted based on longer-term considerations or other information sources.

The availability and accessibility of such information play a crucial role in shaping farmers' knowledge and perceptions of climate change, as well as their adaptive capacity to adopt mitigation strategies (Ado et al., 2019).

Smallholder farmers in this study have identified significant obstacles to adopting Climate-Smart Agriculture (CSA) practices. The primary barriers reported include a lack of knowledge, Lack of resources, and insufficient financial resources. These findings are consistent across different studies, as evidenced by a study conducted in the East Harare zone of Ethiopia by Zeleke et al. (2023), which highlighted limited access to agricultural information and financial constraints as major challenges hindering the implementation of climate change adaptation practices. These barriers are widely documented in the literature on CSA adoption (Finizola e Silva et al., 2024). Addressing these constraints through targeted interventions is crucial for promoting wider CSA uptake. While these barriers pose significant challenges, farmers in the study area have adopted certain CSA practices, with crop rotation being particularly prominent.

Crop rotation is a widely adopted practice due to the significant benefits of food legumes in enhancing soil productivity and fertility. As a crucial element of Climate-Smart Agriculture (CSA), seasonal or annual crop rotation plays a vital role in maintaining soil health. It balances nutrient removal, controls pests and weeds, prevents erosion, improves soil fertility, and sustains soil organic matter. These benefits make crop rotation an essential strategy for promoting sustainable agriculture and resilience to climate change (Okeyo et al., 2020; Jena et al., 2023). The implementation of improved seed varieties as a CSA practice has resulted in increased grain yields among major crops in the study area. These improved crop varieties are characterized by high-quality planting materials with the potential for higher yields and resilience to drought, floods, pests, and diseases This finding aligns with research from Mali's semi-arid region, which demonstrated that farmers' awareness of CSA enhances their adaptive capacity for improved seed (Ouédraogo et al., 2019) The adoption of improved seeds is often driven by the desire for increased productivity and income, particularly in regions vulnerable to climate change (Myeni and Moeletsi, 2023). To address the challenges of CSA and promote the successful implementation of CSA practices, regular and well-grounded interactions between farmers and stakeholders are essential for the effective dissemination of innovations (Ouédraogo et al., 2019; Teklu et al., 2023a). Effective extension services and farmer-to-farmer knowledge exchange can play a critical role in scaling up the adoption of beneficial CSA practices.

The logit regression results indicate that changes in the perceived technology-specific characteristics of CSA innovations increase the likelihood of adoption. Farmers perceptions of CSA innovations, particularly regarding their potential to increase productivity, income, and improve soil moisture, are key drivers of adoption (Teklu et al., 2023b). Our findings reveal a complex relationship between education and CSA adoption. The demographic profile of respondents reveals a low level of formal education, with Koranic education being the primary form of education for a significant portion of the sample. This low level of formal education, particularly the prevalence of Koranic education, may contribute to the counterintuitive negative correlation we observed between education level and the adoption of CSA practices (crop rotation, cover cropping, crop diversification and Improved seed). One plausible explanation is that farmers with primarily Koranic education may have less exposure to information about modern agricultural practices, including these specific CSA techniques. The content of Koranic education, while valuable in other ways, may not directly address the knowledge and skills needed for implementing these particular CSA techniques. Our result is not consistent with studies that have found a positive link between education and CSA adoption (Belay et al., 2017, 2022; Abegunde et al., 2019; Negera et al., 2022; Sanogo et al., 2023). It is also possible that more educated farmers in this region are more likely to adopt different, perhaps more intensive or technologically advanced, agricultural practices not captured in this study, for example, they might be focusing on more intensive irrigation systems. Alternatively, there could be a gap in the type of education or training received, which may not be adequately addressing the benefits and implementation of these particular CSA practices. Perhaps farmers with formal agricultural training are more likely to adopt these practices, while general education level is negatively correlated because those educated farmers are engaging in other non-farm activities due to their education level. It is also possible that more educated farmers, who may have more assets or off-farm income, are more risk-averse and less likely to experiment with new practices until they are widely proven. Additionally, the negative relationship might also be because more educated farmers are less likely to be on the farm due to their engagement in off-farm activities.

The importance of years of experience significantly increases the amount of Agroforestry among farmers in the study area. Human activities contribute to climate change, therefore, experiences in the change of climate observed by farmers, decrease in rainfall, and increased temperature over the years can be a determining factor to see how the damages done through human activities can be repaired through agroforestry is an important way to adapt to climate change. The effect of years of experience implies that farmers with more years of experience are relatively capable of purchasing agricultural input and are more likely to change their farming practices and, therefore, it is important to have more capacity to invest in more climate adaptation strategies taking or adopting more than one CSA practices. Farming experience positively influences Agroforestry CSA adoption and negatively influences conservation tillage, this is because as farmers accumulate experience in farming, they will be able to recognize the benefits of early-adopted CSA practices and will accept additional CSA practices. Our findings are consistent with those of (Chavula et al., 2023), who found that agroforestry adoption positively impacts smallholder farmers' households, also that experience and access to resources are significant factors in the adoption of agroforestry technologies among smallholder farmers. In the context of climate change adaptation, Som Castellano and Moroney (2018) emphasized the role of farming adaptations based on accumulated experience. Ricart et al. (2023) also highlighted that climate change awareness and perceived impacts influence farmers' behavior and experience. Additionally, Amadou et al. (2022) found that farmers' perception and adaptation strategies to climate change in Central Mali are influenced by their years of farming experience.

The adoption of multiple CSA is found to be complementary (Ogisi and Begho, 2023). Furthermore, Table 4 shows that most of the estimated correlation coefficients are significant and positive. Table 4 reports the possibility of positive interdependence among the CSA practices considered in this study. Farmers adopted more than one CSA innovation simultaneously, which is consistent with several studies that claim farmers preferred more than one adoption of CSA practices over piecemeal adoption (Aryal et al., 2018; Teklewold et al., 2019). Pairwise correlation coefficients are significant and positive. This implies that those practices are correlated and can be combined and, hence, are jointly used by the farmers to improve crop yield. All CSA innovations have a complementary effect on the adoption of other CSA innovations that supports the findings of (Kassie et al., 2015; Negera et al., 2022; Ogisi and Begho, 2023) who reported that several practices are interdependent, with some complementary and others substitutable. Senegalese policies should promote integrated approaches to CSA adoption, recognizing the synergies between different practices. Bundling CSA interventions (e.g., improved seeds + crop rotation + CAI) can be more effective than promoting individual practices in isolation.

5 Conclusion and recommendation

Our study explored the factors influencing the adoption of Climate-Smart Agriculture (CSA) practices among smallholder farmers in the Koumpentum region. The most frequently adopted CSA practices were crop rotation (70.4%), improved seed varieties (34.2%), cover cropping (14.5%), crop diversification (13.2%), agroforestry (1.97%), and conservation tillage (14.5%). These findings directly address the research question: Which CSA practices do smallholder farmers who grow food crops in the Koumpentum cluster adopt? The adoption of these practices, particularly crop rotation, suggests a growing awareness among farmers of the need to adapt to climate change. However, the relatively lower adoption rates of other potentially beneficial practices, such as cover cropping, crop diversification, conservation tillage, and Agroforestry, highlight the need for targeted interventions to promote wider uptake.

The study also revealed that CSA practices are often implemented in a complementary manner, with male-headed households predominantly making decisions regarding these practices, underscoring the critical role of gender dynamics in CSA adoption. To enhance adoption, it is crucial to address the specific barriers faced by both men and women farmers. It is recommended that targeted information dissemination of climate information and CSA best practices be developed through multiple channels, including farmer field schools, mobile phone-based platforms, and community radio programs. Information should be accessible to both men and women in their preferred languages and tailored to their specific needs. Also, empowering Women in Agricultural Decision-Making by establishing women's agricultural cooperatives and support groups to provide a platform for women to share knowledge, access resources, and participate meaningfully in decision-making processes related to CSA adoption is important. This requires addressing underlying gender norms that restrict women's access to resources and influence. It is also important to integrate Indigenous Knowledge systems related to climate adaptation into the development and promotion of CSA practices. This can be achieved through participatory workshops and community consultations that value and integrate local perspectives. Given the observed tendency for farmers to adopt CSA practices in combination, agricultural extension services should promote integrated packages of CSA practices tailored to specific agro-ecological zones and farming systems.

The study provides valuable insights into CSA adoption in Koumpentum but has certain limitations. The data focuses on initial adoption and does not directly assess the content of farmers' education, the role of education in sustained adoption, or the adoption of agricultural practices beyond the six considered here. Future research should explore these possibilities to better understand the complex interplay between education, access to resources, and other socio-economic factors influencing CSA adoption decisions. Specifically, studies could investigate the content of local education curricula related to agriculture, examine the adoption of a broader range of agricultural technologies, and analyze the interplay between education, access to resources, and other socio-economic factors in influencing CSA adoption decisions. Further research should also explore the long-term impacts of CSA adoption on farm incomes and assess the effectiveness of different information dissemination strategies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), under the approval number IECICRISAT/30082022/06. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because verbal consent was received.

Author contributions

TE: Conceptualization, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing, Resources. FA: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing, Resources. NT: Validation, Writing – review & editing. SA: Validation, Writing – review & editing. NY: Validation, Writing – review & editing, Resources, Supervision. SK: Funding acquisition, Validation, Writing – review & editing.

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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