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Exploring gender dynamics in climate-smart agriculture adoption: a study in semi-arid Dodoma, Tanzania

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Introduction: Climate change threatens agricultural production, particularly in developing countries, where agriculture supports over 2.5 billion people. Women, who comprise 43% of the agricultural labor force, are particularly vulnerable due to gender inequalities, especially in African societies. While Climate-Smart Agriculture (CSA) offers potential benefits to mitigate the adverse effects of climate change, its benefits are not evenly distributed, with a notable gender gap in adoption.

Methods: This study investigates how gender dynamics influence CSA adoption patterns in Tanzania's semi-arid Dodoma regions, using a mixed-methods approach. The study included a survey of 380 households and focus group discussions with 75 participants.

Results: The results reveal lower CSA adoption among female-headed households (51% non-adopters) compared to male-headed households (38% non-adopters). Probit and Poisson regression analyses identify several key determinants of adoption and adoption intensity, including marital status, livestock ownership, land access, and the availability of extension services. Female-headed households face unique barriers, such as smaller landholdings, labor constraints, and limited access to credit, training, and group membership. The study also highlights the absence of female extension workers in villages.

Discussion: The findings emphasize the need for targeted policy interventions to address these challenges and promote more equitable CSA adoption. These include implementing land reforms to ensure equitable land access for women, designing inclusive training programs that accommodate women's time constraints, and increasing the representation of female extension workers to enhance CSA knowledge dissemination among female farmers. Additionally, improving access to credit facilities for female farmers, strengthening social networks through farmer groups, and improving transport infrastructure to reduce logistical barriers are crucial to further supporting CSA adoption. These targeted interventions are essential for overcoming gender-specific barriers, ensuring that CSA benefits are more equitably distributed, and ultimately supporting sustainable agricultural development.

KEYWORDS

adoption, climate change, climate-smart agriculture, gender, Tanzania

1 Introduction

Climate change threatens agricultural production and food security globally, with particularly severe impacts across arid and semi-arid regions (Kalele et al., 2021). Variability in temperature and precipitation patterns can drastically reduce crop yields, threatening the livelihood of small-scale farmers who depend on agriculture as their main source of income (Arif et al., 2020; Musyimi, 2020). These challenges are exacerbated in developing countries, where over 2.5 billion residents depend on agriculture for their livelihood (Goli et al., 2023). Women, who constitute 43% of the agricultural labor force, are even more vulnerable due to existing gender inequalities, particularly in African societies where gender is a central organizing principle (Babugura, 2021; FAO, 2024; Mekonnen et al., 2019).

Although nature itself does not discriminate, the effects of climate change are not gender-neutral, given the intersection of environmental and social inequities (Reggers, 2019; Huyer et al., 2021). Climate-smart agriculture (CSA) is increasingly recognized as a viable strategy to mitigates the impacts of climate change by improving agricultural productivity, enhancing resilience, and reducing greenhouse gas emissions (Arif et al., 2020; Mpala and Simatele, 2024). CSA practices such as agroforestry, improved crop varieties, integrated soil fertility management, and efficient water use techniques offer considerable potential to improve sustainability and resilience. Agroforestry, for instance, enhances soil fertility and biodiversity, while drought-resistant crop varieties mitigate climate-related yield declines, and efficient water use techniques, like rainwater harvesting, address water scarcity (Lipper et al., 2014; Martey et al., 2020; Partey et al., 2018). Beyond these benefits, CSA practices hold the potential to alleviate gender-specific burdens, providing a wide range of benefits in climate change adaptation (Huyer et al., 2024; Jones et al., 2023). For instance, agroforestry not only enhances soil fertility but also provides biodiversity benefits and reduces women's workloads by supplying fuelwood, mitigating the risks associated with long-distance collection, such as gender-based violence (Jones et al., 2023).

Despite its potential, CSA's benefits are not equitably distributed, primarily due to persistent gender gaps in agriculture. Studies indicate that globally, women in agriculture have less access to productive resources, financial capital, and advisory services than men, and their labor-intensive contributions are often undervalued (Nelson and Huyer, 2016). The persistent gender gap in agriculture is not only a matter of social equity and justice but also a significant economic concern. Closing this gender gap in agriculture could increase agricultural productivity, reducing global hunger by 100–150 million people (Villarreal, 2013). Given the gendered nature of climate change impacts, it is crucial to improve the effectiveness of CSA interventions to ensure both environmental and social equity (FAO, 2015; Jones et al., 2023).

Across Africa, female farmers, especially those in rural areas, face numerous constraints that increase their vulnerability to climate change effects (Babugura, 2021). In Tanzania, where agriculture employs 70% of the population, the impact of climate change is profound (Brüssow et al., 2017). Smallholder farmers, the backbone of Tanzanian agriculture are especially vulnerable due to their limited adaptive capacity and reliance on rain-fed agriculture. Climate change has already negatively impacted crop production in the country, with droughts and extreme weather events reducing maize and sorghum yields, especially in arid regions like Dodoma and Tabora (Kahimba et al., 2015). By 2050, maize, sorghum, and rice yields are projected to decline by 13, 8.8, and 7.6%, respectively (Rowhani et al., 2011). Women, who make up over 80% of the Tanzanian agricultural workforce, face even greater challenges due to institutional barriers and traditional gender norms that limit their access to resources and decision-making power (Akram-Lodhi and Komba, 2018; Jones et al., 2023).

While gender-specific barriers in agriculture are well-documented, gaps remain in understanding how these dynamics influence CSA implementation specifically. Awiti (2022) highlights that there remain critical evidence gaps in understanding how gender dynamics shape CSA adoption. For example, factors such as intra-household decision-making process, gendered perceptions of climate change, and unequal access to adaptation resources are poorly understood in the African context. This underscores the need to explore gender dynamics more deeply to address the barriers hindering female farmers from benefiting equally from CSA practices. Despite efforts to implement gender-sensitive agricultural policies, little evidence exists that gender has been effectively integrated into Tanzania's CSA policy framework (Van Aelst and Holvoet, 2016). The lack of a clear and intersectional approach to gender within CSA policies further exacerbates gender disparities in access to resources and opportunities. To promote more equitable access to CSA benefits, it is essential to enhance both the conceptual clarity and practical implementation of gender-sensitive, context-specific strategies that address these disparities.

To address these gaps, this study draws on the gender equality and empowerment frameworks by Huyer et al. (2021), which emphasize decision-making power, access to resources, and institutional and social norms as critical factors promoting gender equity in climate resilience. By exploring how these elements influence the uptake of CSA practices in Tanzania, this study aims to enhance the understanding of the gendered dynamics in CSA adoption. Specifically, the study seeks to identify the determinants of CSA adoption and intensity, explore gender-specific challenges in CSA implementation, and examine how gender norms and intra-household dynamics shape decision-making related to CSA practices. The study addresses three key research questions: (1) What socioeconomic, institutional, and contextual factors drive CSA adoption and intensity? (2) What gender-specific challenges do different household heads face when adopting CSA? (3) How do gender norms and intra-household dynamics shape decision-making related to CSA adoption and farm activities? By addressing these questions, the study aims to inform the development of targeted interventions that prioritize those most impacted, ensuring CSA benefits are distributed in a way that not only promotes sustainable agricultural development but also advances gender equality in climate resilience.

2 Materials and methods

2.1 Study area

This study was conducted in the Dodoma region of Tanzania, specifically the Chamwino and Kongwa districts. The region is characterized by a semi-arid climate, erratic rainfall, low soil fertility, making it highly vulnerable to the impacts of climate change. Located in central Tanzania at an altitude of 1,000–1,500 meters above sea level, the region experiences annual rainfall ranging from 400 to 800 mm (Mkonda and He, 2018; Awoke et al., 2023). Agriculture is the primary livelihood activity in the region, with most households engaged in subsistence farming, often supplemented by livestock keeping. The main crops grown include maize, sorghum, millet, and groundnuts, all of which are highly vulnerable to the impacts of climate variability. The region is one of the most drought-affected and food-insecure in Tanzania, where prolonged dry spells and fluctuating rainfall patterns threaten crop yields and exacerbate food insecurity (Brüssow et al., 2017).

2.2 Sampling design and data collection

A mixed methods approach was used, combining a household survey with focus group discussions (FGDs) to obtain comprehensive data on gender roles in CSA. The study villages were purposefully selected with the support of the agricultural extension officers, lead farmers, village leaders, and the Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF) staff. Through the Africa RISING project, CIFOR-ICRAF introduced CSA interventions in some of these study villages. A total of six villages were selected for this study: Ilolo and Chololo from Chamwino district and Mlali, Nghumbi, Iduo, and Sagara from Kongwa district. To capture diverse perspectives, the selection included a mix of villages with and without exposure to CSA interventions. Ilolo, Nghumbi, and Mlali were part of the Africa RISING project, which introduced CSA practices to enhance climate adaptation among subsistence farmers. In contrast, Chololo, Iduo, and Sagara were selected as non-intervention villages. The selection criteria for these villages considered factors such as the extent of agricultural activity, socioeconomic diversity, and the presence or absence of CSA interventions. This comparative approach allowed the study to encompass a broad range of experiences and challenges faced in semi-arid zones. Although the inclusion of CSA intervention villages may introduce potential bias, these villages were included to generate critical insights into CSA adoption and its implications. Including non-intervention villages with similar climatic vulnerabilities provides a balanced perspective and mitigates the risk of overrepresentation of intervention outcomes. Furthermore, the shared climatic conditions and agricultural challenges across neighboring villages in the Dodoma region enhance the generalizability of the findings, providing valuable lessons for other semi-arid regions facing similar climate-related risks. Data was collected from January to April 2024 with all interviews were conducted in Kiswahili, the national language.

2.2.1 Quantitative data collection

2.2.1.1 Household survey

The household survey comprised a sample of 380 households, with either the head or the spouse of each household being interviewed using a structured and open-ended questionnaire facilitated by the Kobotoolbox. Stratified sampling was employed to ensure a balanced representation of households from each village. Within each stratum, simple random sampling was employed to ensure that every household had an equal chance of being selected, regardless of household head gender. Female-headed households constitute 32% of the total sample. Most respondents were married male-headed households, with only 9% of married households being female-headed. These latter cases occur when the husband is away for an extended period, comes from a different region or tribe, or, in the case of polygamy, where the husband is frequently absent (Figure 1).

Households adopting at least one CSA practice were categorized as CSA adopters. Seven CSA practices were evaluated, including tree intercropping, tied ridges, contour farming, Chololo pits, manure application, the use of drought-tolerant seeds, and inorganic fertilizer (Table 1). The survey encompassed binary, multi-choice, and open-ended questions designed to capture relevant, diverse issues. Before the study started, all enumerators underwent comprehensive training, thus ensuring proficiency with the data collection tool. All enumerators held at least a bachelor's degree and were proficient Kiswahili speakers. Additionally, the survey was pre-tested with individuals who were not part of the sample, thus familiarizing enumerators with the survey and ensuring the elicitation of meaningful responses.

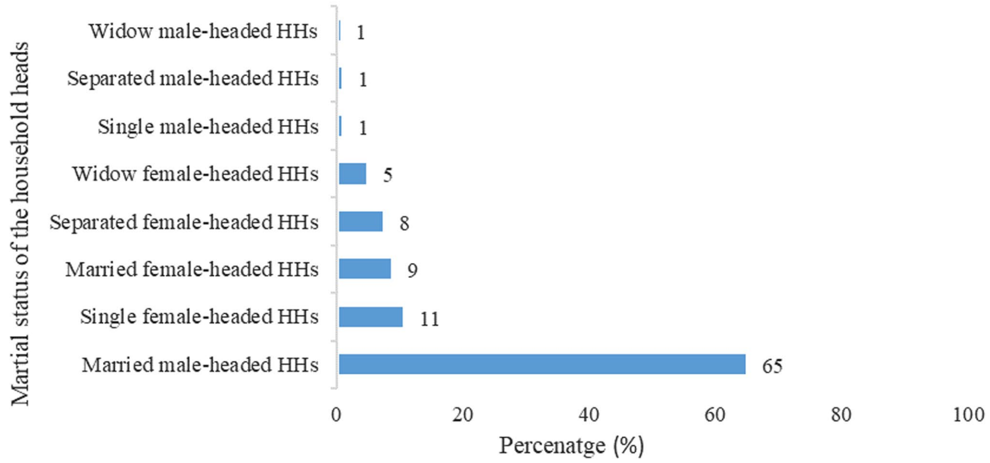

FIGURE 1
Marital status and gender of the household (HH) heads (n = 380).

TABLE 1 Climate-smart agriculture (CSA) practices and components.

CSA practices	Description	CSA component
Tree intercropping	Involves growing trees and crops on the same land; also referred as fertilizer tree intercropping	Enhances biodiversity, improves soil fertility, reduces soil erosion, and enhances water retention (Sileshi et al., 2023)
Tied ridges	Water and soil water conservation techniques used to capture and retain water. Ties create small basins that slow water runoff, allowing more time for water to infiltrate into the soil	Captures rainwater, reduces water runoff, improves water infiltration, increases water availability (Njeru et al., 2016).
Contour farming	Plowing and planting crops and shrubs along to land contours to reduce erosion	Reduces soil erosion, slows water runoff, enhances water conservation, maintains fertility (Kizito et al., 2022)
Chololo pits	Digging small circular pits on farmland to capture and store water	Improves soil moisture, reduces erosion, increases water infiltration, and enhances crop yields (Gamba et al., 2020).
Manure application	Adding animal manure to the soil to improve soil fertility	Enriches soil with nutrients, improves soil structure, increases water retention (Schaller et al., 2017).
Use of drought-tolerant seeds	Planting crop varieties that withstand dry conditions and water stress	Ensures better crop yields in drought, increases resilience to water stress, enhances food security, promotes sustainable farming (Martey et al., 2020).

2.2.2 Qualitative data collection

2.2.2.1 Focus group discussion

Focus group discussions conducted in the second stage helped to address and triangulate findings from the household surveys. Focus group discussion participants were selected from all survey participants based on the advice of extension workers, lead farmers, and village leaders, ensuring a representative sampling of CSA adopters and non-adopters alongside balanced gender representation. Held in the same six villages as the survey, FGDs comprised 12 sessions (six female-only focus groups and six male-only focus groups) totaling 75 participants. A gender-sensitive approach was used, with FGDs segregated by gender to encourage open discussion, particularly among female participants (Ngigi et al., 2017). This amplifies the voices of all participants while recognizing the importance of gender dynamics in agriculture.

Following Hennink's (2013) guidelines, each FGD comprised 6–8 participants, combining both CSA adopters and non-adopters, ensuring an optimal environment for discussion while accommodating variations in group dynamics. Data collection included audio recording, note-taking, and participant observation (Nyumba et al., 2018). FGDs were moderated by the researcher in English with simultaneous translation into Kiswahili; each session lasted 2–3 h.

Guiding questions included: (1) What challenges do female farmers face in CSA adoption? (2) How do women and men perceive the impact of climate change and adaptation strategies? (3) How are decisions made in married households? (4) Are there disparities between men and women in accessing resources like training and credit? (5) What roles are assigned to men and women in implementing CSA? and (6) How can support systems work to address gender disparities? Questions were tailored based on the gender of the participants. For instance, question one was mainly addressed to female farmers, while other questions were posed differently to male and female participants.

2.3 Data analysis

A mixed-method approach was applied, combining econometric regression (probit and count models) with qualitative content analysis to gain more insights (Bryman, 2017).

2.3.1 Quantitative data analysis

Quantitative data were analyzed using probit and Poisson regression models to identify the determinants of CSA adoption and adoption intensity. Key variables include household head age, education level, farm-holding size, off-farm income, and extension services visits (Table 2). *T*-tests were performed to assess if there were statistically significant differences between female- and male-headed households for continuous variables. A chi-square test examined the association between categorical variables, like household head gender and CSA adoption.

2.3.1.1 Probit regression: determinants of adoption of CSA in female- and male-headed households

To explore factors influencing CSA adoption, a probit regression analysis was conducted; this is common when studying determinants of agricultural technology adoption (Mthethwa et al., 2022; Kimbi et al., 2020). It is suitable if the dependent variable is binary and based on the cumulative distribution function (CDF) of the standard normal distribution. Probit is appropriate here because it addresses heteroscedasticity issues and meets the assumption of a cumulative normal distribution (Kimbi et al., 2020).

The model assumes that unobserved continuous latent variables determine the binary outcome (Mthethwa et al., 2022). Here, the dependent variable is CSA adoption (0 = non-adopter, 1 = adopter). Following Mthethwa et al. (2022) and Kimbi et al. (2020), the model is specified as Equation (1):

$$CSA_i = F\left(X_i\beta\right) + \varepsilon_i \qquad (1)$$

where, CSA_i is 1 if the household adopted CSA and 0 otherwise; X_i is the set of independent variables; β is the vector of coefficients estimated using maximum likelihood; ε_i is the error term, assumed to be normally distributed with mean 0 and variance 1 ($\varepsilon \sim n = 0.1$).

Given that the probit model estimates provide only one direction of effects, following Asante et al. (2024), the marginal effects were calculated to interpret the actual change in adoption probability attributable to changes in the independent variables. The marginal effects are computed as Equation (2):

$$ME = \beta_i \varnothing\left(z\right) \qquad (2)$$

TABLE 2 Description of variables.

Variables	Description of variables	Expected outcome
Marital status	Dummy (1 = Married, 0 otherwise)	+/−
Age	Household head age (number of years)	+/−
Education level	Household head number of school years	+
Livestock ownership	Dummy (1 = yes, 0 otherwise)	+
Market walking distance	Walking distance in minutes	−
Distance from home to farm	Walking distance in minutes	−
Distance to nearest tap water	Walking distance in minutes	−
Farming experience	Number of years	+/−
Farm land holding size	Measure in hectares (ha)	+
Land access	Dummy (1 = if land is leased, 0 otherwise)	−
Labor is hired	Dummy (1 = yes, 0 otherwise)	+/−
Extension service availability	Dummy (1 = yes, 0 otherwise)	+
Number of extension service visit	Number of visits per year	+
Training access	Dummy (1 = if participated in training, 0 otherwise)	+
Farmer group membership	Dummy (1 = yes, 0 otherwise)	+/−

Where: β_i are the coefficients and $\phi(z)$ refers to the standard cumulative normal distribution.

Additionally, sub-sample analysis based on household head gender was performed to identify the distinct factors influencing adoption between female- and male-headed households.

2.3.1.2 Poisson regression model specification

After identifying those factors influencing CSA adoption, count regression models were used to uncover the determinants of adoption intensity, a common approach in related studies (Ojo et al., 2023; Thinda et al., 2020). These include the Poisson Regression Model (PRM), the Negative Binomial Regression Model (NBRM), the Zero Inflated Negative Binomial (ZINB), and the Zero Inflated Poisson (ZIP).

The Poisson regression model was selected here to assess the determinants of CSA adoption intensity because the initial diagnostic, including a Pearson goodness-of-fit test ($x^2 = 357.51$, $p = 0.408$) and a likelihood ratio test for overdispersion (LR test of delta = 0, $p = 0.500$), indicated adequate model fit and no significant evidence of dispersion (Cameron and Trivedi, 2013). Moreover, PRM is designed for analyzing non-negative integer responses, thus appropriate for this study. Hence, the PRM is specified as Equation (3):

$$f\left(y_i|X_i\right) = \frac{e^{-\mu}\mu_i^{yi}}{y_i!}, y_i = 0,1,2 \quad (3)$$

Subsequently, disaggregated analyses by household head gender identifies those factors determining the CSA adoption intensity within each group, providing insights into the influence of household composition. All analyses were conducted using STATA 18.

2.3.2 Qualitative data analysis

The qualitative data from FGDs were analyzed using qualitative content analysis, a systematic approach to identifying and categorizing patterns, themes, and insights. MAXQDA, a software tool designed for qualitative and mixed-method research, was used (Udo and Stefan, 2019). All audio recordings from FGDs were transcribed to ensure an accurate representation of the discussions. Subsequently, transcripts were systematically coded using MAXQDA. This coding process involved assigning labels to meaningful units of text that were relevant to the research questions. Identified codes were then examined to identify comprehensive themes, which were further categorized to provide a structured understanding of the data (Chibowa et al., 2020).

Key themes emerging from the analysis included intra-household decision-making, adoption, access to resources, perception of CSA, farm activities, and gender-specific adoption challenges. Interpretation of these themes was undertaken to extract a deeper understanding of the participants' perspectives, contextualizing them within the broader framework of gender dynamics and CSA patterns.

3 Results

3.1 Socioeconomic and demographic characteristics of the households

The analysis examines the differences between female- and male-headed households across various socioeconomic variables. Female-headed households are younger, have smaller farms, and have less annual farm income; all these differences are statistically significant (Table 3).

3.2 Adoption of CSA technologies by female- and male-headed household

Results reveal a significant gender difference in CSA adoption. About 51% of female-headed households did not adopt any of the CSA practices, compared to 38% of male-headed households (Figure 2). The Pearson chi-square test confirms a significant correlation between gender and CSA adoption ($x^2 = 5.9514$, $p = 0.015$), indicating lower adoption rates among female-headed households.

Both female- and male-headed households preferred specific CSA practices, with manure use, drought-tolerant seeds, and tree intercropping being the top three practices (Figure 2). Contour farming, Chololo pits, and tied ridges were also adopted, although to a lesser extent: these are labor-intensive practices, thus not favored by households with less labor access or low income. Further, the majority prefer less labor-intensive practices like tree intercropping or manure than soil water conservation practices.

Additionally, inorganic fertilizer application was notably low, below 3% adoption among both household types. FGDs highlight that this low adoption rate is driven by the perception and long-held belief in the community that industrial fertilizers have long-term adverse effects on soil health. Thus, farmers prefer organic manure to enhance soil fertility.

TABLE 3 Descriptive statistics- socioeconomic and demographic characteristics of the households (HHs).

Variables	Pooled sample	Female-headed households (n = 122)	Male-headed households (n = 258)	
Categorical variables	**Percent**	**Percent**	**Percent**	**Pearson chi²**
Marital status	73.68	27.05	95.74	201.72***
Off-farm income	54.21	57.38	52.71	0.146
Livestock ownership	81.05	77.05	82.95	1.88
Extension service availability	57.11	42.62	43.02	0.94**
Farmer group membership	72.11	31.97	25.97	0.22
Training access CSA knowledge dissemination	18.00	14.00	21.00	0.205
Continuous variables	**Mean**	**Mean**	**Mean**	***T*-test**
Age	48.48	46.43	49.45	2.210***
Education level	5.82	5.40	6.02	1.133
Market distance	29.40	30.45	28.89	−0.425
Distance from home to farm	61.32	63.92	60.10	−0.802
Distance to nearest water tap	17.98	17.47	18.22	0.239
Farming experience	26.73	25.98	27.09	0.800
Farmland holding size	2.58	1.68	3.01	4.630***
annual farm income (USD)	418.19	272.65	487.01	2.280***
Number of extension service visits	3.34	2.95	3.53	0.702

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

3.3 Determinants of adoption and intensity of adoption

3.3.1 Determinants of adoption between male- and female-headed farm households

A probit regression was used to evaluate factors affecting the adoption of CSA practices; the model has a good fit, given that the Wald chi2 is statistically significant for the pooled sample and the sub-groups (see Table 4). Married households are 10.4% more likely to adopt CSA practices than unmarried households across the pooled sample. Livestock ownership also positively influences CSA adoption, with a more substantial impact in male-headed households, where the probability of CSA adoption is 10.8% higher for households that own livestock. Additionally, market walking distance positively influences CSA adoption in female-headed households, where a unit increase in market distance results in a 0.1% increase in the likelihood of CSA adoption.

Conversely, distance from home to farm is a significant barrier to CSA adoption, decreasing adoption rates by 0.2% for the pooled sample, in female-headed households, as well as in male-headed households per minute increase in farm distance. Similarly, longer distances to water taps negatively influence CSA adoption.

Accessing land through lease arrangements is another barrier to CSA adoption, where the likelihood of adoption decreased by 9.3% across the pooled households and by 14.7% in male-headed households when land was accessed through a lease arrangement. In contrast, the ability to hire labor positively influenced adoption in female-headed households, with a 6.8% increase in the probability of adoption when hired labor was available.

The availability of extension services emerged as a vital factor positively affecting CSA adoption across the pooled households, with a notable impact among male-headed households. Households with access to extension service availability had a 15.5% higher probability of CSA adoption across the pooled sample and a 20% higher probability in male-headed households. Similarly, access to training substantially increases adoption by 29.3% in female-headed households and 38.1% in male-headed households. Furthermore, farmer group membership increased the likelihood of CSA adoption by 17.8% in female-headed households and 17.6% in male-headed households. This underscores the importance of social networks and collective learning for disseminating CSA practices regardless of gender.

3.3.2 Determinants of the intensity of adoption between male and female-head households

A Poisson regression helps to understand the determinants of CSA adoption intensity; here, it is significant (Prob > chi^2 = 0.000) and well-fitting (Table 5). We reported the regression coefficients as incidence rate ratios (IRRs), which were subsequently converted into percentages to enhance interpretability. Education level is positively correlated with adoption intensity. Each additional year increases adoption intensity by 1.8% for the pooled sample, with 2.4% increases for female-headed households. This underscores the vital role of education in empowering female farmers and facilitating their engagement with new agricultural innovations.

Market walking distance also positively influences adoption intensity: each additional minute of walking increases adoption intensity by 0.4% across the pooled sample and 0.5% for male-headed households. Conversely, longer distances from the homestead to the farm and to the nearest water tap negatively impact the intensity of CSA adoption. A one-minute increase in distance to the nearest water tap decreases adoption intensity by 1.6% across the pooled sample,

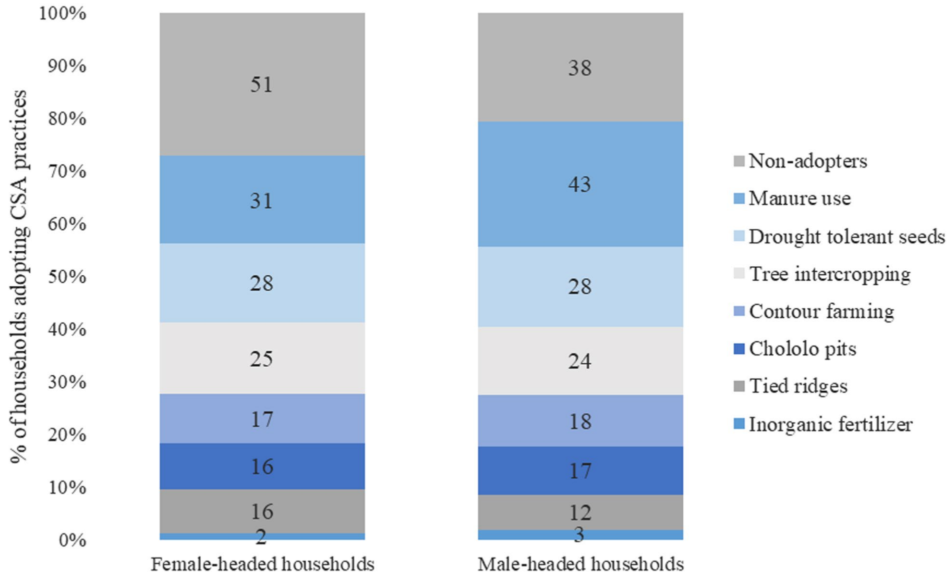

FIGURE 2
Adoption rate of CSA practices among female- (n = 122) and male-headed households (n = 258). The figure shows the percentage distribution of households adopting CSA.

3.6% in female-headed households, and 1.4% in male-headed households. Similarly, a one-minute increase in farm distance reduces adoption intensity by 0.5% across the pooled sample, female-headed households and, in male-headed households. This reflects how logistical burdens add to the constraints of female farmers, who bear the burden of fetching water in both single and married households.

Land access and farm holding size also have substantial effects, particularly for male-headed households. A one-hectare increase in farm holding size increases the intensity of CSA adoption by 3% across the pooled sample and by 3.3% in male-headed households, indicating that large land resource facilitates better implementation of CSA practices. In contrast, land access through leasing reduces adoption intensity by 14.7% across the pooled sample and by 26.7% for male-headed households.

The availability of extension services, the number of extension service visits, training access, and farmer group memberships are all positively associated with CSA adoption intensity. Extension service availability increases the adoption intensity by 110% across the pooled sample, by 6.5% in female-headed households, and by 129.3% in male-headed households. Each additional extension visit increases adoption intensity by 0.8% across the pooled sample and by 0.6% in male-headed households. Additionally, training access is significant, increasing CSA adoption intensity by 89.2% across pooled households, by 12.1% in female-headed households and by 82.6% in female-headed households. Finally, farmer group membership positively influences CSA adoption intensity by 76.4% across pooled households, 53.9% in female- and 62.7% in male-headed households.

3.4 Gender-specific challenges in terms of adoption

The household survey and FGDs reveal gender-specific challenges in adopting CSA. The findings highlight that female farmers are often perceived as more proactive and responsive to implementing new agricultural practices than their male counterparts. This is especially pronounced among mothers, who face additional vulnerabilities due to their dual roles as caregivers and primary managers of household food security. For example, focus group participants in Ilolo village noted that during drought seasons, husbands frequently migrate to towns for work, leaving women to manage both farming and household responsibilities. As the primary individuals responsible for ensuring their families have enough food, women bear the brunt of food shortages, which increases their vulnerability to climate change impacts and drives their willingness to adopt CSA practices to improve food security and mitigate the challenges they face. Despite female farmers' responsiveness, disparities observed within agricultural contexts, particularly in access to resources such as land access, labor, credit access, group membership, and training opportunities. Even with advancements toward gender inclusiveness, inequalities continue, often favoring males with greater resource access and control over resources. These barriers and their influence on CSA adoption are further explained below.

land access: land access remains a significant barrier for female-headed households. Male farmers typically own more land than female farmers. A t-test reveals that female-headed households own significantly less land, averaging 1.8 ha, compared to male-headed households, who own an average of 3 ha ($p < 0.01$). Furthermore, female-headed households cultivate significantly less land (1.6 ha; $p < 0.01$) on average than their male counterparts (2.8 ha). This difference indicates systematic favoritism in land distribution, where male heirs typically receive larger proportions of land.

Labor: labor constraints and the need for initial investment were major challenges for female-headed households. Labor shortages are frequently stated as a major barrier to implementing CSA practices like tied ridges or Chololo-pit, which are both labor-intensive and physically demanding. Probit regression analysis (Table 4) also

TABLE 4 Results of probit regression factors affecting HH adoption of CSA.

Variables	Pooled sample		Female-headed households		Male-headed households	
	Coefficient (SE)	Marginal effect (SE)	Coefficient (SE)	Marginal effect (SE)	Coefficient (SE)	Marginal effect (SE)
Marital status	0.405 (0.184)**	0.104 (0.047)**	−0.117 (0.397)	−0.028 (0.094)	−0.152 (0.399)	−0.036 (0.096)
Age	0.004 (0.012)	0.001 (0.003)	−0.035 (0.032)	−0.008 (0.008)	0.004 (0.014)	0.001 (0.003)
Education level	0.007 (0.015)	0.002 (0.004)	0.006 (0.023)	0.002 (0.006)	0.004 (0.021)	0.001 (0.005)
Livestock's ownership	0.341 (0.189)*	0.088 (0.048)*	0.465 (0.348)	0.110 (0.082)	0.447 (0.250)*	0.108 (0.059)*
Market walking distance	0.005 (0.002)**	0.001 (0.001)**	0.011 (0.004)***	0.003 (0.001)***	0.002 (0.003)	0.001 (0.001)
Distance from home to farm	−0.007 (0.002)***	−0.002 (0.000)***	−0.008 (0.004)**	−0.002 (0.001)**	−0.009 (0.003)***	−0.002 (0.001)***
Distance to nearest tap water	−0.013 (0.004)***	−0.003 (0.001)***	−0.032 (0.013)***	−0.007 (0.003)***	−0.012 (0.004)***	−0.003 (0.001)***
Farming experience	−0.002 (0.012)	−0.001 (0.003)	0.035 (0.033)	0.008 (0.008)	−0.003 (0.014)	−0.001 (0.003)
Farm land holding size	0.041 (0.032)	0.011 (0.008)	0.187 (0.157)	0.044 (0.036)	0.041 (0.030)	0.010 (0.007)
Land access	−0.361 (0.163)**	−0.093 (0.041)**	0.285 (0.304)	0.068 (0.072)	−0.611 (0.204)***	−0.147 (0.047)***
Labor is hired	0.263 (0.173)	0.068 (0.044)	0.610 (0.350)*	0.145 (0.082)*	0.167 (0.214)	0.040 (0.051)
Extension service availability	0.602 (0.202)**	0.155 (0.050)**	0.163 (0.352)	0.039 (0.083)	0.829 (0.258)***	0.200 (0.057)***
No extension service visit	0.011 (0.014)	0.003 (0.004)	0.017 (0.020)	0.004 (0.005)	0.007 (0.018)	0.002 (0.004)
Training access	1.187 (0.294)***	0.306 (0.070)***	1.235 (0.420)***	0.293 (0.087)***	1.583 (0.490)***	0.381 (0.112)***
HH farmer group memberships	0.638 (0.237)***	0.165 (0.060)***	0.753 (0.413)*	0.178 (0.094)*	0.732 (0.279)**	0.176 (0.067)***
Constant	−0.084 (0.576)	0.104 (0.047)	−0.709 (0.974)		0.592 (0.659)	−0.036 (0.096)
Wald chi^2	118.75		53.15		95.69	
Prob > chi^2	0.000		0.000		0.000	
Pseudo R^2	0.3244		0.389		0.3644	
Log-likelihood	−165.025		−51.66		−104.331	

IRR (Incidence rate ratio) and marginal effects are reported with standard errors (SE) in parentheses. Statistical significance levels are indicated as follows: ***p < 0.01, **p < 0.05, *p < 0.1.

indicates that the availability of hired labor positively influences the adoption of CSA, implying that female-headed households able to afford hired labor are more likely to adopt CSA than those who cannot.

Credit access and group membership: in terms of access to credit and group membership, male farmers are typically favored, largely due to land and property ownership; these represent security for loan applications. Given that women typically do not own such assets, limiting their access to credit poses a major barrier to women. The disparity in credit access between female and male farmers was evident in an Iduo village farmer group: of 33 members—22 females and 11 males—only 9% of female members possessed the required documents for loan applications compared to 100% of male members. Given that the group sought a collective loan, they had to kick out all the female farmers who lacked all the necessary documents to acquire the loan successfully. Thus, gender disparities in access to credit resources and group membership were highlighted and exacerbated.

Training opportunities: focus group discussions revealed that female participants are often more responsive to training opportunities than their male counterparts. However, approximately 60% of participants acknowledged the assumption that women usually lack time to attend training due to household responsibilities, leading to potential biases in participant selection. Despite this, the discussions also highlighted an encouraging shift, with women actively increasingly engaging in CSA-related opportunities. For instance, survey data showed that 20.16% of male-headed households and 14.75% of female-headed households received training on CSA knowledge dissemination.

Absence of female extension workers: it is important to note the observed absence of female extension workers in the study villages, which may limit the accessibility and effectiveness of training for female farmers. This gap highlights the need for more inclusive approaches in extension service delivery. Incorporating more female extension workers into the agricultural support system would help create a more supportive and effective environment for female farmers, ensuring that CSA practices are accessible and beneficial to both male- and female-headed households.

3.5 Gender dynamics on-farm activities intra-household decision-making

Women are widely recognized for their significant contribution to farm labor. The survey findings confirm that women are heavily involved in many farm activities, either working independently or jointly with men. In some cases, female farmers are equally engaged in farm activities, if not more than their male counterparts (Figure 3). For instance, land preparation, fertilizer application, weeding, sowing, and harvesting are conducted jointly, with women often participating independently and a small percentage of tasks being performed solely by men.

TABLE 5 Poisson regression result: determinants of the intensity of adoption.

Variables	Pooled sample		Female-headed HHs		Male-headed HHs	
	IRR (SE)	Marginal effects (SE)	IRR (SE)	Marginal effects (SE)	IRR (SE)	Marginal effects (SE)
Marital status	1.037 (0.109)	0.052 (0.150)	1.129 (0.235)	0.165 (0.282)	0.789 (0.264)	−0.345 (0.490)
Age	1.001 (0.007)	0.002 (0.010)	0.975 (0.021)	−0.034 (0.029)	1.003 (0.007)	0.004 (0.010)
Education level	1.018 (0.006)**	0.025 (0.008)**	1.024 (0.009)***	0.033 (0.012)***	1.008 (0.015)	0.011 (0.022)
Livestock's ownership	1.094 (0.179)	0.128 (0.232)	1.248 (0.383)	0.302 (0.417)	1.035 (0.187)	0.051 (0.262)
Market walking distance	1.004 (0.001)***	0.006 (0.001)***	1.003 (0.002)	0.003 (0.003)	1.005 (0.001)***	0.007 (0.001)***
Distance from home to farm	0.995 (0.001)***	−0.007 (0.002)***	0.995 (0.002)**	−0.007 (0.003)**	0.995 (0.001)***	−0.008 (0.002)***
Distance to nearest tap water	0.984 (0.004)***	−0.023 (0.005)***	0.964 (0.013)***	−0.050 (0.018)***	0.986 (0.003)***	−0.020 (0.005)***
Farming experience	1.002 (0.006)	0.003 (0.009)	1.025 (0.020)	0.034 (0.027)	1.000 (0.006)	0.000 (0.009)
Farmland holding size	1.030 (0.009)***	0.042 (0.012)***	1.068 (0.052)	0.089 (0.066)	1.033 (0.009)***	0.047 (0.013)***
Land access	0.853 (0.081)*	−0.226 (0.134)*	1.284 (0.267)	0.340 (0.286)	0.733 (0.077)***	−0.451 (0.150)***
If labor is hired	1.126 (0.102)	0.169 (0.128)	1.055 (0.218)	0.073 (0.279)	1.146 (0.122)	0.198 (0.154)
Extension service availability	2.100 (0.263)***	1.057 (0.187)***	1.655 (0.475)*	0.685 (0.386)*	2.293 (0.314)***	1.207 (0.213)***
Number of extension service visits	1.008 (0.003)**	0.012 (0.005)**	1.004 (0.008)	0.005 (0.011)	1.006 (0.004)*	0.009 (0.005)*
Training access	1.892 (0.193)***	0.908 (0.144)***	2.121 (0.449)***	1.023 (0.298)***	1.826 (0.206)***	0.876 (0.162)***
HH farmer group memberships	1.764 (0.193)***	0.809 (0.155)***	2.539 (0.594)***	1.268 (0.345)***	1.627 (0.203)***	0.708 (0.179)***
Constant	0.680 (0.239)		0.859 (0.732)		1.057 (0.513)	
Wald chi^2	531.57		164.71		421.96	
Prob > chi^2	0.000		0.000		0.000	
Pseudo R^2	0.300		0.357		0.294	
Log-likelihood	−478.310		147.217		−320.784	

Incidence rate ratio (IRR) and marginal effects are reported with standard errors (SE) in parentheses. Statistical significance levels are indicated as follows: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Despite their significant contribution to farm activities, decision-making power typically remains with men. While women may express interest in CSA innovations, the final decisions are usually made by male household heads, which can hinder the adoption of new practices. For example, in married households, in decisions about crop type selection (Figure 4), are made independently by women 8% of the time, by men 36% of the time, and jointly 56% of the time. This decision-making dynamic can affect the adoption of CSA practices, as the male head's preferences and willingness to adopt new practices may influence their implementation. For instance, in the case of tree intercropping, if the husband is not supportive of integrating or planting trees, it could prevent the adoption of such practices, even if the spouse is interested.

Similar patterns of male dominance are seen in other decision-making areas, such as agricultural product selling and farm income control. For instance, survey findings show that in decisions about what or how much to sell, 6% of the time, women decide independently; 23% of the time, men decide; and 71% of the time, decisions are made jointly. The same pattern applies to farm income control, where male heads have more power (Figure 4). Resource ownership, such as land, and prevailing social norms play a significant role in shaping these decisions. Property rights and traditional gender roles often limit women's autonomy, reinforcing male dominance in decision-making. In summary, while women are key to farming activities, men largely control decision-making, influencing CSA adoption and resource use.

4 Discussion

This study, guided by the gender equality and empowerment framework of Huyer et al. (2021), explores the determinants of CSA adoption with a focus on gender-specific challenges, decision-making, and access to resource. The findings, derived from household survey data and further enriched through FGDs, reveal significant gendered disparities in adoption patterns.

4.1 Determinates of adoption and gender-specific challenges

The determinants of CSA adoption and intensity reveal a complex interplay of socioeconomic, institutional, and logistical factors, with notable gender-specific differences. Factors such as landholding size, marital status, education, and market proximity drive adoption rates; however, these are exacerbated by gendered barriers, particularly for female-headed households.

Female-headed households face considerable barriers, including limited land, labor, and capital access. On average, female farmers own less land than their male counterparts, limiting their ability to implement land-intensive CSA practices (Quisumbing et al., 2014). This disparity, deeply rooted in gender-biased inheritance practices, constrains women's capacity to implement practices requiring larger land areas, such as agroforestry (Quisumbing et al., 2014; Hailemariam et al., 2024). While Tanzania's legal reforms aim to improve women's land rights, gaps in implementation persist, highlighting the need for awareness campaigns and stronger enforcement of policies (Teklewold et al., 2020). Financial constraints further hinder adoption; limited access to credit, frequently tied to land ownership as collateral, reinforces male control over agricultural investments, restricting women's ability to adopt CSA technologies. This limited access to credit also leads to the exclusion of women from farmer groups, as observed in one of the study villages, diminishing their social status and limiting their access to collective resources and networks. Consequently, women are marginalized within their communities, which not only affects their capacity to adopt CSA practices but also reduces their influence in agricultural decision-making. Furthermore, their exclusion from farmer groups restricts their opportunities for knowledge exchange and access to support systems, further isolating them from agricultural innovations. These findings align with Kiptot and Franzel (2012) who noted that female farmers often opt for low-cost, less labor-intensive practices, which may not provide sufficient resilience to climate change. Labor availability also plays a critical role. Female-headed households with better access to hired labor are more likely to adopt CSA practices, reflecting the interdependence of financial resources, credit access, and labor constraints (Perelli et al., 2024). Additionally, membership in farmer group is a key enabler, enhancing access to inputs, knowledge, and support networks a finding consistent with Fischer and Qaim (2012). The impact of livestock ownership on CSA adoption is consistent with previous research indicating that livestock can be a critical asset in agricultural decision-making (Mujeyi et al., 2021). This livestock ownership provides the financial security necessary to increase the likelihood of CSA adoption, increasing the likelihood of purchasing agricultural inputs (e.g., improved cultivars, mineral fertilizer, and manure). However, this impact is more pronounced in male-headed households, likely due to traditional gender roles that grant male farmers greater control over productive resources (Doss, 2018).

Social and institutional norms further shape CSA adoption patterns. Married households demonstrate higher adoption rates due to shared resources, pooled labor, and enhanced social capital, which facilitate implementation (Beyene et al., 2017). These households often have better access to farmer groups, which provide additional support network for CSA implementation (Sanogo et al., 2023). However, gender biases in agricultural programs often limit women's participation in such networks, as male farmers are prioritized for training and resource distribution (Ragasa et al., 2013). Despite women's responsiveness to climate adaptation strategies, they are often marginalized in the distribution of training and resources. To address this, expanding the inclusivity of agricultural programs is critical to ensure female farmers have equal access to knowledge, resources, and support networks (Chibowa et al., 2020). One key solution lies in empowering female agricultural extension workers, who are currently underrepresented in the study areas. Female extension workers are better positioned to address the unique challenges women face, such as cultural norms and gendered communication barriers that may limit women's participation when services are predominantly delivered by male extension workers (Tsige et al., 2020; Duffy et al., 2021). The incorporation of more female extension workers into the agricultural support system would create a more supportive and effective environment for female farmers, ensuring that CSA practices are accessible and beneficial to both male- and female-headed households.

Education further enhances the effectiveness of such interventions, particularly for female-headed households. Educated farmers are better equipped to access, interpret, and apply innovative practices, increasing adoption. This aligns with Bongole (2023), who emphasizes education's role in empowering farmers to adopt agricultural innovations effectively. Moreover, the positive influence of extension services and farmer group membership on CSA adoption underscores the importance of inclusive support networks and educational resources (Ragasa et al., 2013; Teklewold et al., 2013).

Interestingly, greater market distance is associated with higher CSA adoption among female-headed households, which may seem counterintuitive compared to studies emphasizing the benefits of proximity to markets for agricultural innovation uptake. Similar findings have been observed by Khan et al. (2017) and Zerihun et al. (2014), who

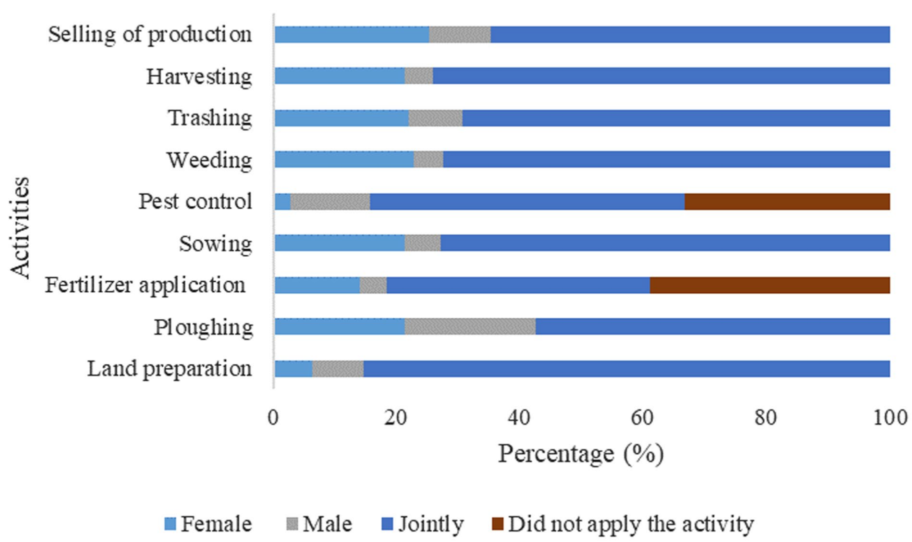

FIGURE 3
Farm activities categorized by gender (n = 380).

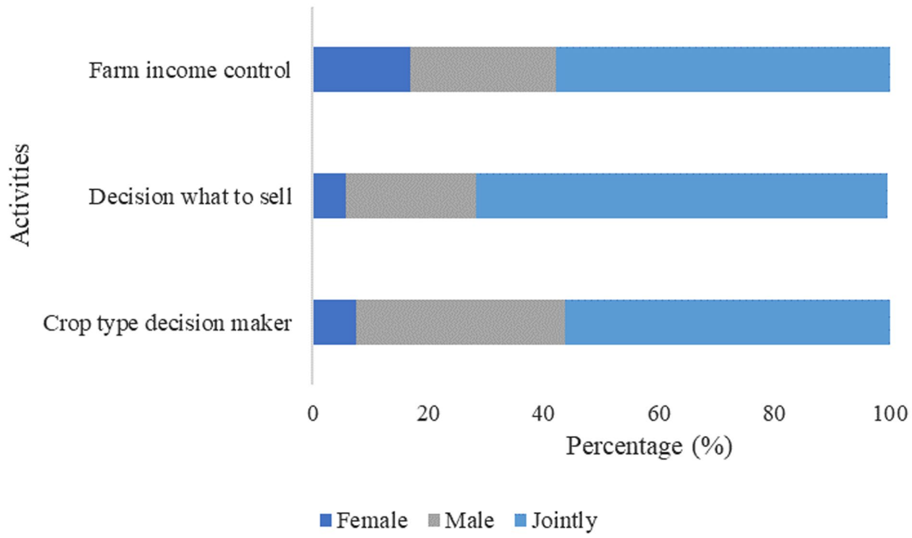

FIGURE 4
Intra-household decision-making power in married households (n = 277 married households).

found that market distance positively influences practices like agroforestry, whereas Kifle et al. (2022) reported the opposite. This discrepancy may be explained by the unique constraints faced by female-headed households in remote areas, where higher transaction costs and logistical constraints promote reliance on locally available, low-cost practices like manure (38% adoption in this study) over market-dependent inputs like inorganic fertilizers (2–3%). In addition to farmers perceptions of adverse effects of inorganic fertilizer on soil health, high costs and, transport barriers may further limits it is adoption (Meinzen-Dick et al., 2014). The role of local interventions is also critical, For instance, For example, agroforestry adoption was higher in Ilolo (67%), a remote village benefiting from targeted interventions, compared to Chololo (7%), which is closer to markets. These findings highlight the need to evaluate CSA practices on a case-by-case basis, as adoption patterns are shaped by a complex interplay of local conditions and interventions. Furthermore other logistical constraints, like distances to farms and water, negatively impact adoption across both genders, consistent with Abegunde et al. (2020) and Teklewold et al. (2013).

Overall, these findings underscore gender-specific challenges in CSA adoption are shaped by broader structural factors such as land access, financial resources, institutional and social norms. These insights highlight the importance of designing gender-sensitive policies that address the distinct needs of female farmers and leverage support networks to promote equitable adoption of CSA practices.

4.2 Gender dynamics, on-farm activities, and intra-household decision-making power

The study explores gender dynamics in farm activities and intra-household decision-making power concerning CSA. Despite women's extensive involvement in farm labor and farm activity in ensuring household food security, decision-making power remains predominantly with male household heads, limiting women's autonomy in adopting CSA Male dominance is particularly evident in decisions regarding practice preferences, crop types, income control, and the allocation of resources for adoption. These findings are consistent with broader literature highlighting the link between male control over key resources such as land, livestock, and income and their dominant influence on agricultural adoption decisions (Meinzen-Dick et al., 2014; Perelli et al., 2024). Power asymmetries in decision-making often stem from entrenched cultural norms and unequal resource access. In the study area, traditional norms position men as primary decision-makers, leaving women with limited autonomy to adopt CSA practices. Perelli et al. (2024) found that in Tanzania and across Sub-Saharan Africa, men typically control decisions related to production and the adoption of new farming practices. Similarly, Acosta et al. (2020) argue that joint decision-making in many African households rarely reflects equitable participation, as men often retain the final authority. These patterns underscore how resource control shapes power dynamics within households, with women's limited access to assets such as land, livestock or income further diminishing women's decision power.

Addressing intra-household power imbalances requires targeted and culturally sensitive interventions. Evidence from Lambrecht et al. (2016) showed that synchronized agricultural training that includes both couples has enhanced shared decision-making and increased the adoption rate of climate adaptation strategies. Furthermore, aligning knowledge of CSA technologies between partners can reduce intra-household conflicts and foster collaborative decision-making. Initiatives that bridge the knowledge gap and empower women in male-headed households could significantly enhance joint decision-making and, in turn, encourage the adoption of CSA practices.

4.3 Implications for policy and recommendations

The gender-specific findings of this study highlight the necessity for targeted interventions to address the unique challenges faced by female- and male-headed households. For sustainable and inclusive agricultural development, policymakers must address these challenges with specific strategies.

- *Land reforms:* implement policies that ensure equitable land distribution and secure land rights for women. Along with legal reforms made to improve female access to land, community awareness programs can help challenge traditional inheritance practices that favor male heirs.
- *Inclusive training programs:* design and implement training programs that are accessible to both household heads and their spouses, preventing intra-household conflicts over CSA adoption. Encouraging the participation of both genders in advanced agricultural training and ensuring that training schedules accommodate women's time constraints.
- *Gender responsive extension services:* increase the number of female agricultural extension workers to address gender-specific challenges and improve women's access to CSA knowledge and technologies. This aligns with findings on the underrepresentation of female extension workers and their potential role in empowering women farmers.
- *Accessible credit facilities:* establish financial services tailored to female farmers, particularly those without property, by reducing collateral requirements and offering credit guarantees to improve women's access to financial services.
- *Strengthening social networks:* promote collective learning platforms, such as farmer groups, to disseminate CSA practices and support female farmers.
- *Improved Infrastructure and logistics:* enhance transport infrastructure to ease access to essential resources, reducing the time and burden on farmers, particularly women, thus encouraging CSA adoption.

5 Conclusion

This study offers a comprehensive analysis of gender dynamics in CSA adoption, providing critical insights for building climate resilience and advancing gender equality. While existing literature acknowledges gender disparities in agriculture, this study uniquely identifies the specific factors influencing both CSA adoption and its intensity. It reveals how socioeconomic, institutional, social norms, and logistical factors shape adoption patterns, with female-headed households often facing greater barriers due to limited access to essential resources such as land, labor, capital, and credit. While female-headed households exhibit lower CSA adoption rates, largely due to these resource constraints, they demonstrate high responsiveness to CSA opportunities, especially when interventions are tailored to their specific needs. This highlights the importance of addressing gendered barriers to ensure more widespread adoption among female farmers. The study underscores the critical role of education, extension services, and farmer group membership in enhancing CSA adoption. However, the underrepresentation of female extension workers exacerbates these challenges, limiting women's access to training and support. Empowering female extension workers and ensuring inclusive, gender-responsive extension services are vital for fostering equitable CSA adoption. Additionally, asset ownership such as landholding size and livestock ownership positively influences CSA adoption intensity in male-headed households but not in female-headed ones. This points to the need for targeted interventions, such as land reforms, to ensure equitable access to land for women and address the gendered disparities in asset ownership. The findings also highlight the need for interventions that promote joint decision-making within households, ensuring equal access to resources and knowledge for both spouses. Addressing intra-household power imbalances and promoting collaboration between spouses in CSA-related decisions could substantially increase adoption rates. Furthermore, improving access to credit, as well as infrastructure like transportation, is essential for facilitating CSA adoption, particularly among women who often face additional logistical and financial barriers. In conclusion, the study calls for a more inclusive approach to CSA promotion, one that acknowledges the specific challenges faced by female farmers while recognizing their potential as key agents of climate resilience. To ensure CSA adoption is both widespread and effective, policies must be gender-sensitive, focusing on improving land access, education, extension services, credit access, and support networks for female farmers. By addressing these challenges and empowering women through targeted interventions, the agricultural sector can become more resilient, equitable, and sustainable, contributing to the broader goals of sustainable development and gender equality.

Data availability statement

The raw data supporting the conclusions of this article will be made available upon request from the corresponding author Mahlet-Degefu.Awoke@zalf.de.

Ethics statement

This research is part of the PhD project "Developing an Assessment Framework along the Agroforestry: Food security Nexus: Sustainable land Strategies for people-centered Land Restoration in Tanzania," which was reviewed and approved by the National research Registration Committee (NRCC) of the Tanzania Commission Science and Technology (COSTECH). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. KL: Conceptualization, Supervision, Writing – review & editing. AK: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. ML: Conceptualization, Supervision, Writing – review & editing. BS: Conceptualization, Methodology, Writing – review & editing. KB: Writing – review & editing. JH: Methodology, Writing – review & editing. SS: Funding acquisition, Supervision, 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 authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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