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RECEIVED 15 September 2025

REVISED 14 October 2025

ACCEPTED 05 November 2025

PUBLISHED 19 November 2025

CITATION

Katunzi A, Mlengera N, Mng'ong'o M,
Mwamlima B, Mvile B, Mtama J and
Lukasumbusa R (2025) Enhancing climate
resilience of smallholder farmers through
conservation agriculture in the southern
highlands of Tanzania.
Front. Sustain. Food Syst. 9:1706205.
doi: 10.3389/fsufs.2025.1706205

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Enhancing climate resilience of smallholder farmers through conservation agriculture in the southern highlands of Tanzania

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Conservation Agriculture (CA) offers a promising pathway for enhancing climate resilience and productivity among smallholder farmers in the Southern Highlands of Tanzania. This study assessed how farmers in Mbeya region and surrounding areas use CA practices to adapt to climate change and variability between 2015 and 2024. Temperature and rainfall data were analyzed alongside on-station and on-farm CA trials. Results showed a warming trend (0.040 °C/year for maximum and 0.026 °C/year for minimum temperatures) and variable rainfall patterns (903.9–1518.7 mm annually). In 2021, the maize yields under planting basins (8.5 t/ha) outperformed no-till (6.2 t/ha) and conventional ox-ploughing (6.0 t/ha). CA practices reduced production costs and increased profit margins for maize (USD 526.9 vs. 176.6) and beans (USD 917.4 vs. 376.3). Despite increased adoption of minimum tillage and residue retention, barriers included residue burning, crop-livestock competition, and limited access to inputs. Findings underscore CA's role in sustainable intensification and call for policy support, tailored extension, and institutional coordination to scale CA for climate-smart intervention in farming systems.

KEYWORDS

conservation agriculture, smallholder farmer, climate change and variability, southern highlands of Tanzania, consensus discussion

1 Introduction

Many parts of Tanzania are food insecure due to low agricultural productivity caused by negative consequences of climate change and variability (Mang'anya, 2018; Randell et al., 2022). Over 80% of Tanzania's food is produced by smallholder farmers, most of them being women and youth (Gayo and Ngongolo, 2025). These farmers are primary victims of the impacts of climate change and variability. The solution has been for farmers to shift from one field to another looking for more fertile land and water. This practice has exacerbated deforestation and land degradation in many regions of Tanzania (Mugasha and Katani, 2016). The field experiment was centred on conservation agriculture (CA) practices to improve climate resilience of smallholder farmers in the Southern Highlands Zone (SHZ) of Tanzania. The CA is built on three interlinked principles of minimum soil disturbances, maintaining a permanent organic soil cover and crop rotation. These CA practices are considered as sustainable agricultural intensification strategies in crop production.

CA has numerous benefits economically, socially and environmentally, its adoption in Sub-Saharan Africa (SSA) and Africa in general is reported to be low particularly for smallholder farms (Araya et al., 2024). Among the factors attributing to low adoption include limited access to inputs (including reduced tillage implements), competing uses for crop residues, and the need for knowledge and capacity building on CA technologies. Efforts to evaluate and promote CA practices/technologies through on station and on farm demonstrations have been done by Tanzania Agricultural Research Institute (TARI)—Uyole started in 1999 (Mlengera et al., 2018). However, CA adoption among the surrounding communities was observed to gain a steady increase around the year 2010.

In recent years, due to climate change and variability, rainfall has decreased whilst temperature has increased (Luhunga, 2025). The frequency and intensity of extreme weather events (floods, droughts and strong winds) have increased and presents serious challenges to smallholder farmers. The only option to fight against unfavourable consequences of climate change and variability in farming systems is the adaptation approach. The field experiment employed CA techniques by integrating proven and practical interventions at farm level targeting to reduce the impacts of climate change whilst improving food production. Proven CA interventions are available in Tanzania though the problem has been to coordinate them for impactful resilience at farm level.

In Tanzania, efforts have been applied to combat the undesirable consequences of climate change and variability in agriculture, though with difficulties (George and Kangalawe, 2024). The difficulties come from smallholder farmers' access to technology, education on climate resilience and their minimal involvement in addressing climate change related challenges. The study was aligned with the national priorities to ensure food and nutrition security through implementation of CA practices and technologies in Southern Highlands of Tanzania. Also, Tanzania adheres to international commitments to reduce greenhouse gas emission in agriculture. Recently, Tanzania launched the National Guide on Mitigating Consequences of Climate Change and Variability in Agriculture (Okuthe et al., 2025).

This research integrates on-station and on-farm CA interventions with localized analysis of climate trends (2015–2024) and assessment of economic status of different farming systems to evaluate climate resilience and crop productivity. In the Southern Highlands of Tanzania, particularly Mbeya region the study combined empirical field experiments with farmer-prioritized CA practices and a comparative cost–benefit analysis of CA versus conventional maize and beans production practices. The study links to the potential of CA practices in mitigating climate change impacts and brings to tangible farmer outcomes (yields, incomes, adoption barriers) within the same study design, creating an evidence package tailored for national uptake and local scaling. We hypothesized that the adoption of CA practices enhances yield stability and profitability while reducing vulnerability to climatic fluctuations among smallholder farmers.

The study clearly address gaps by producing context-specific, actionable evidence for smallholder-dominated landscapes where CA adoption remains low despite of the proven benefits (Makate et al., 2025). The findings are useful to different stakeholders including farmers and will enable higher CA uptake among women and youth farmers who produce the majority of Tanzania's food (Nchanji et al., 2025). The results are targeted to support national climate-smart

agriculture priorities and international mitigation commitments by demonstrating how farm-level CA adoption can simultaneously increase productivity, strengthen climate resilience, and reduce impacts of climate change in different farming systems.

This study therefore evaluates climatic trends, agronomic and economic performance, and adoption barriers of CA to guide evidence-based scaling in the Southern Highlands of Tanzania aimed at generating knowledge to agricultural stakeholders that will increase resilience to climate change impacts, hence sustainable crop production.

2 Materials and methods

2.1 Description of the study area

The study was carried out at the Tanzania Agricultural Research Institute (TARI Uyole) and in three villages of Muvwa, Njelenje, and Mapogoro located in Mshewe ward Tanzania (Figure 1). TARI Uyole lies approximately 8 kilometers east of Mbeya city, along the Tanzania–Zambia highway, positioned at latitude 8°55'S and longitude 33°22'E. Situated at an elevation of roughly 1,798 meters above sea level, the area experiences a consistently cool climate. Temperatures can fall to −7 °C during June and July, and the region receives an average annual rainfall of about 965 mm, with the rainy season typically extending from November to May (Authority, T. M., 2022; Magang et al., 2024). The selected villages were included in the study to gather and analyze data on CA practices adopted by smallholder farmers to enhance resilience within local farming systems. Soils at Uyole are volcanic in origin, generally slightly acidic (pH ~ 6.5). A pedological study identified sandy loam textures in the topsoil and sandy clay loam in the subsoil. Organic carbon levels range from very low to medium, and cation exchange capacity (CEC) is medium to high (15–34 cmol(c)/kg), indicating moderate fertility. According to USDA Soil Taxonomy the soils of Uyole are classified as Pumiceous, Mixed, Superactive, Isothermic, Typic Hapludand (Mtama et al., 2018).

2.2 Research perspective and design

The study adopted a pragmatic research perspective, chosen for its suitability in addressing real-world challenges through the integration of diverse methodological approaches (Kaushik and Walsh, 2019). A cross-sectional design was applied to capture data at a specific point in time (Spector, 2019). Additionally, time series analysis statistical technique typically aligned with longitudinal research designs (Wang et al., 2017) was employed to examine temperature and rainfall patterns in the study area over the period from 2015 to 2024.

2.3 Data collection of rainfall and temperature

Guided by a pragmatic perspective, the research integrated a cross-sectional capture of CA practices with a time-series analysis of climate variability (2015–2024). Temperature and rainfall data were

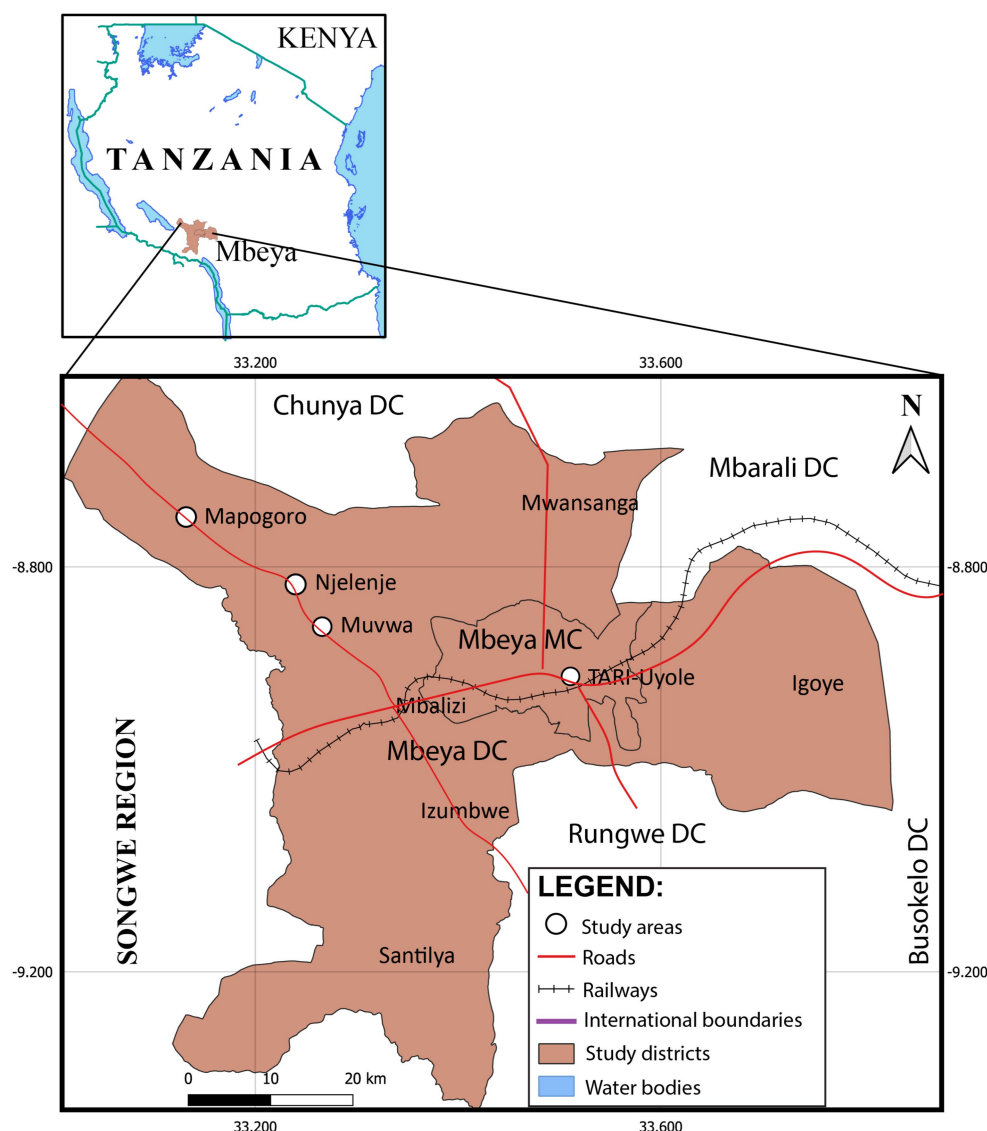


FIGURE 1
The map of Tanzania showing the study areas.

obtained from the National Aeronautics and Space Administration (NASA) and Tanzania Meteorological Authority (TMA) office in Mbeya, respectively. The yearly datasets were compiled and subsequently analyzed using python method to derive the annual trend values of the climatic conditions.

2.4 Field data collection

Before data collection commenced, ethical clearance was obtained from the Mbeya City Council and village leaders granted community consent. All individual participants were provided a written informed consent, and protocols ensured voluntary participation, confidentiality of responses and secure storage of data. Field data were collected through a combination of CA trials, weather records from the TARI Uyole station, and in-depth interviews with key informants. This multi-source approach was

designed to capture diverse perspectives on both climatic conditions and CA practices. These methods were selected based on prior training sessions delivered to various CA stakeholders, particularly farmers from nearby villages. In addition to evaluating the performance of these techniques, the study explored barriers to the adoption of CA technologies and practices. To enrich this understanding, qualitative interviews were conducted with individuals who possess deep local knowledge such as community leaders, agricultural professionals, and farmers familiar with CA activities in selected study villages. These interviews aimed to gather firsthand insights into the practical realities, perceptions, and challenges surrounding CA implementation. For the on-station CA trials, a range of planting techniques/practices were tested including farmer practice (ox-ploughing), planting basins, no-till, and tractor-ripping. These treatments were allocated in a randomized complete block design (RCBD), replicated three times.

2.4.1 Individual general interviews

During the initial phase of the study, we conducted field visits to the selected areas to gain insight into the local context and familiarize ourselves with the living conditions and farming practices of individual households. This stage primarily engaged members of village-based farmer groups, such as Farmer Group Meetings (FGMs) and other local associations. The objective was to deepen our understanding of the social, cultural, and economic dynamics within these farming communities.

In total, 75 farmers participated in the study across Mapogoro, Njelenje, and Muvwa villages thus 25 farmers from each location. We successfully conducted face-to-face interviews with all participants, focusing on those who were actively adopting and applying CA practices and technologies. Although gender was not a central focus based on findings from (Banjarnahor, 2014), which indicated it was not a major concern in this region we still aimed for balanced representation of both men and women across all villages. Prior to the main interviews, the questionnaire was piloted with a small group to ensure clarity and relevance. The survey primarily explored the types of CA practices being used by smallholder farmers and the barriers they face in implementation. Additional insights were gathered through open-ended questions, which allowed farmers to elaborate on their views and experiences related to the study's objectives. Beyond capturing general livelihood patterns and farming systems, the questionnaire served as a flexible tool for covering unexpected themes and perspectives directly from the farmers themselves.

2.4.2 Consensus discussion

The study employed a consensus discussions (CDs) method, a tailored variation of the conventional focus group discussion (FGD) technique (Bachtiar et al., 2024). This approach was used to gather insights into CA practices among smallholder farmers in the target areas. Before participating in group meetings, we held informal conversations with selected CA farmers and conducted direct field observations. These activities helped us assess the types of CA practices being implemented and identify the key challenges affecting adoption in the region. This preliminary commitment was essential for building a deeper understanding of the local context and the stakeholders involved. During village visits and interactive sessions, we also documented the presence of institutions actively supporting CA initiatives. These organizations typically offered services and carried out field-based activities aimed at assisting farmers engaged in CA. Their involvement was instrumental in encouraging consistent and meaningful participation from individual CA farmers throughout the project.

In selecting farmers for participation, gender considerations were prioritized by ensuring that enough women were actively engaged in group discussions. These discussions were conducted in each village, using an interactive approach that encouraged farmers to share their perspectives and beliefs regarding CA practices. The primary objectives of these group sessions were two folds: to rapidly gather insights from a wider pool of farmers, and to identify variations in CA-related experiences and perceptions across different groups within Mshewe ward. This group-level data complemented the information obtained from individual interviews, enabling a more comprehensive assessment of broader trends and patterns.

The CDs were conducted twice in each of the 3 study villages: Mapogoro, Njelenje, and Muvwa resulting in a total of 6 sessions.

Each group comprised 8 participants, including both male and female farmers practicing CA, yielding 16 respondents per village and a total of 48 participants across all sites. The discussions aimed to engage farmers critically, reflecting on current CA practices and dissemination strategies. Participants were encouraged to recall both past and ongoing experiences with CA and to propose innovations for future implementation. The sessions also explored strategies for CA development and promotion, with emphasis on improving access to essential farm resources such as equipment, services, inputs, and market channels. A key focus of the discussions was the role of institutional support in advancing CA adoption among smallholder farmers. Particular attention was given to the perceived benefits and challenges of CA based on individual farm experiences. Additional topics included farmers' knowledge of CA principles, crop residue management, yield performance, labor efficiency, farm size considerations, crop selection, and climate change adaptation strategies.

The CDs served as a triangulation method to observe how farmers interacted within group settings and to verify whether key topics were consistently raised and agreed upon across different groups (Donkoh and Mensah, 2023). These sessions provided valuable, in-depth insights into smallholder farmers' perspectives in each village, while also revealing patterns of communication and group dynamics. Participants included CA farmers who were actively involved in disseminating CA technologies, as well as those who had not adopted or had discontinued CA practices. To validate and enrich the data gathered during discussions, follow-up farm visits were conducted. These visits allowed for direct observation and documentation of site-specific CA practices and technologies being implemented such as cover cropping, agroforestry, crop rotation, intercropping, ripping, and tied ridges which integrated into the broader analysis presented in the discussion section.

2.5 Data analysis and statistical procedures

The analysis were undertaken using analysis of variance (ANOVA) aided by GenStat to analyze the maize yield data from the on-station experiments at TARI Uyole. GenStat's mixed-model (REML) routines accounted for random effects of blocks/replications, seasons, and farm sites. Also, SPSS (version 20, IBM, New York, USA) was used to analyze both semi-qualitative and quantitative datasets. Descriptive statistics such as percentages and frequencies were calculated to profile adoption levels and socio-economic characteristics of CA implementers in the study villages. Chi-square tests assessed significant differences in CA practices or technologies and challenges facing smallholder farmers in Mbeya rural. On the other hand cost-benefit analyses was derived from total production costs and earnings on investment for CA versus conventional practices.

3 Results and discussion

3.1 The trend of temperature and rainfall in the study area

The graph shows warming trends in the region over the past decade (Figure 2). The red line, representing maximum temperatures,

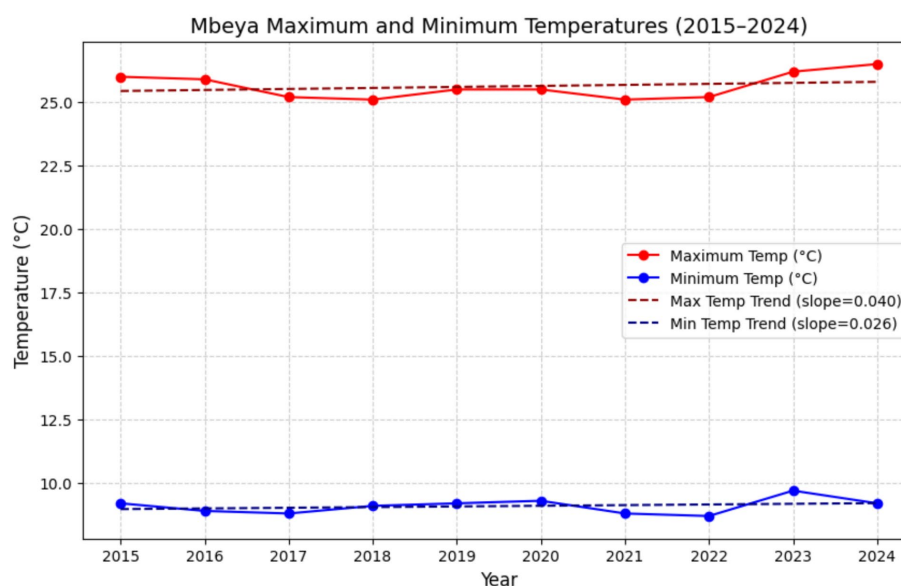


FIGURE 2

The trend of temperature for the period of 2015–2024.

and the blue line, representing minimum temperatures, both show gradual increases, with trend line slopes of $0.040^{\circ}\text{C}/\text{year}$ and $0.026^{\circ}\text{C}/\text{year}$, respectively. This indicates that while both daytime highs and nighttime lows are rising, the increase in maximum temperatures is slightly more pronounced. Such warming though modest can have meaningful implications for agriculture in Mbeya region.

Elevated maximum temperatures may accelerate crop maturation, increase evapotranspiration rates, and intensify heat stress during sensitive growth stages, particularly in maize and beans farming systems. Meanwhile, rising minimum temperatures could influence germination, pest dynamics, and soil microbial activity. For practitioners of CA, these trends suggest a need to adjust transplanting schedules and water management strategies to mitigate thermal stress. From a policy and extension perspective, the data supports the urgency of climate-smart interventions, including heat-tolerant crop varieties, adaptive agronomic calendars, and region-specific outreach programs. This temperature trajectory reinforces the importance of integrating localized climate data into agricultural planning and farmer training programs.

In Mbeya region, the annual rainfall from 2015 to 2024 reveals a pattern of significant inter-annual variability, with rainfall amounts fluctuating rather than following a consistent upward or downward trend (Figure 3). The lowest recorded rainfall occurred in 2015 at 903.9 mm, while the highest was in 2024, reaching 1518.7 mm, a striking increase that may reflect shifting climatic dynamics or anomalous weather conditions. Notably, years like 2020 and 2022 also saw elevated rainfall levels above 1,100 mm, suggesting intermittent spikes rather than gradual accumulation. This variability poses both challenges and opportunities for agricultural planning in the region. In years of high rainfall, farmers may benefit from extended water availability, but they also face increased risks of flooding, nutrient leaching, and delayed field operations. Conversely, lower rainfall demands more precise water-use strategies, drought-resilient crop

choices, and efficient irrigation systems. The graph of rainfall data offers a powerful visual tool for enabling stakeholders to better anticipate rainfall extremes and develop context-specific response strategies.

In the Southern Highlands of Tanzania especially Mbeya region, temperature and rainfall trends from 2015 to 2024 present notable agronomic and strategic considerations. A gradual increase in both maximum and minimum temperatures though relatively modest indicates a warming trajectory with potential impacts on crop phenology, soil moisture retention, and pest dynamics. Rising maximum temperatures may hasten crop development, potentially reducing the grain-filling duration in maize and disrupting pod formation in beans. Concurrently, elevated minimum temperatures could influence germination rates and promote the spread of pests and diseases, particularly within humid microenvironments fostered by mulch and cover crops.

The rainfall data, marked by significant inter-annual variability, reinforces the value of CA practices. Years like 2020, 2022, and especially 2024 with rainfall exceeding 1,200 mm highlight the risk of waterlogging, nutrient leaching, and delayed field operations. In contrast, drier years such as 2015 and 2018 emphasize the importance of moisture retention and drought resilience. Techniques like minimum tillage, permanent soil cover, and crop rotation as core principles of CA help buffer against these extremes by improving infiltration, reducing runoff, and enhancing soil structure. For extension officers and farmer trainers, these trends underscore the need to promote adaptive planting calendars, resilient seed varieties, and localized weather forecasting. The empirical evidence supports the formulation of bilingual instructional resources designed to enhance farmers' capacity to interpret agro-climatic signals and implement adaptive agronomic strategies accordingly. These inter-annual fluctuations illustrate the exposure of Mbeya's rainfed systems to climatic shocks, reinforcing the role of CA in improving water infiltration and soil moisture conservation.

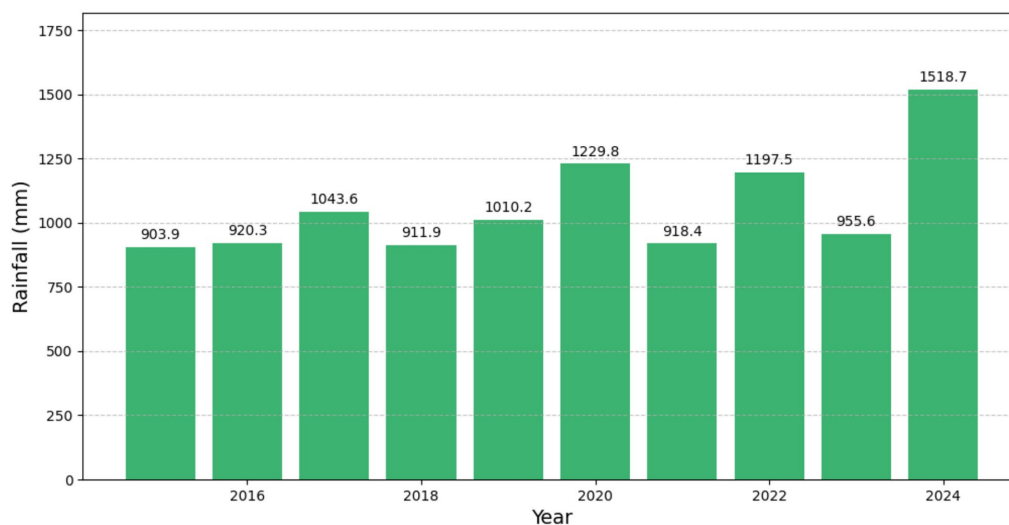


FIGURE 3
The trend of rainfall for the period of 2015–2024.

3.2 Conservation agriculture principles and practices

The on-station evaluation and on-farm adoption results of CA technologies and practices for TARI Uyole and Mbeya rural villages of Muvwa, Njelenje, and Mapogoro, respectively, are presented in [Tables 1 and 2](#). The maize yield results for the cropping season 2021 indicated significant difference in the basin treatment when compared to no-till and farmers practice (ox-plough). Such results might be influenced by low rainfall when compared to other cropping seasons of 2020 and 2024 that recorded high rainfall. Though generally there is no significant difference on evaluated CA technologies and practices in terms of yields, the advantage is mostly based on the production costs which are normally low regarding CA practices ([Table 3](#)).

The dataset ([Table 2](#)) presents a cross-sectional comparison of the CA principles and practices across three villages of Mshewe wards in Tanzania. The total sample size of 75 farmers with 25 per village were fully involved in the study. The practices assessed include cover cropping, mulching, ox-ripping, crop rotation, intercropping, minimum tillage, and herbicide application. Adoption rates were analyzed using chi-square tests to determine whether statistically significant differences exist among the villages. The results indicate near-universal adoption of certain practices specifically, the use of ox-rippers and minimum tillage across all villages ([Table 2](#)). These findings suggest that these technologies are either mandated through extension programs or have achieved widespread farmer acceptance due to their agronomic benefits, such as reduced soil disturbance and improved water retention.

Practices such as cover cropping, mulching, and crop rotation also show high adoption rates ($\geq 88\%$) across all villages, with chi-square values indicating no statistically significant differences ($p > 0.05$). This uniformity implies that these practices are well-integrated into local farming systems, possibly due to their compatibility with existing crop calendars and resource availability. In contrast, intercropping and herbicide application exhibit more variability. Intercropping adoption ranges from 60% in Mapogoro to 84% in Muvwa, while herbicide use varies from 72 to 92%. Although these differences are not statistically

TABLE 1 TARI Uyole maize yield results.

Cropping seasons	2021	2022	2024
Treatments	Maize yield (t/ha)		
Farmer practice (Ox-plough)	6.0 a	5.4 ab	5.7 a
No-till	6.2 a	6.9 b	6.5 a
Tractor ripper	7.3 ab	4.9 a	6.6 a
Basins	8.5 b	4.6 a	
Grand mean	7.1	5.5	6.3
CV	14.8	14.2	20.3
P Probability	0.075	0.042	0.6

significant ($p = 0.143$ and $p = 0.171$, respectively), they may reflect underlying differences in agro-ecological conditions, farmer knowledge, or access to inputs. For example, higher intercropping rates in Muvwa could be linked to land fragmentation or a greater emphasis on biodiversity, while herbicide use may correlate with weed pressure or market access to chemical inputs. From a methodological standpoint, the use of chi-square tests is appropriate for categorical data, though the relatively small sample size per village ($n = 25$) may limit statistical power. The absence of significant p -values across all practices suggests homogeneity in CA adoption, but further inferential analysis such as logistic regression or multivariate clustering could uncover latent patterns or predictors of adoption.

3.3 Economic analysis of conservation agriculture versus conventional farming

The comparative analysis of production costs and returns for beans and maize reveals a compelling case for adopting CA practices ([Table 3](#)). For beans, although CA incurs slightly higher costs in land preparation and seed inputs, it significantly reduces expenses in ploughing, weeding, and pest control. Notably, harrowing is

TABLE 2 CA principles and practices used by farmers on their farms in Mshewe ward.

CA principles and practices used by farmers	Total, <i>n</i> (%) [*]	Mapogoro, <i>n</i> (%) ^{**}	Njelenje, <i>n</i> (%) ^{**}	Muvwa, <i>n</i> (%) ^{**}	Chi-square	<i>p</i> -value ^{***}
Type of CA practices						
Cover crops	71 (94)	23 (92)	24 (96)	24 (96)	0.528	0.768
Mulching	70 (93)	22 (88)	24 (96)	24 (96)	1.714	0.424
Ox-ripper	75 (100)	25 (100)	25 (100)	25 (100)	NIL	NIL
Crop rotation	70 (93)	22 (88)	24 (96)	24 (96)	1.714	0.424
Intercropping	52 (69)	15 (60)	16 (64)	21 (84)	4.888	0.143
Minimum tillage	75 (100)	25 (100)	25 (100)	25 (100)	NIL	NIL
Spraying herbicides	62 (82)	18 (72)	23 (92)	21 (84)	5.356	0.171

^{*}As a percentage of the total number of respondents (*n* = 75); ^{**}As a percentage of the total number of respondents in each village (*n* = 25); ^{***}*p*-value for comparing CA practices used by farmers for each practice.

TABLE 3 Economic analysis of CA versus conventional farming practices.

Operations	Beans production cost (USD/ha)		Maize production cost (USD/ha)	
	Conventional practice	CA practice	Conventional practice	CA Practice
Land preparation	65.2	86.2	56.8	32.5
Ploughing/Ripping	66.6	33.8	71.2	25.6
Harrowing	41.4	-	45.5	-
Fertilizer	93.2	93.2	204.6	204.6
Seeds	113.6	142.1	47.7	54.6
Planting	80.5	80.2	75.1	93.9
Weeding	78.3	56.4	92.1	62.9
Control of insect pest	51.6	30.2	34.7	24.3
Harvesting	62.2	59.9	61.0	85.2
Total production costs	652.7	623.5	688.7	583.6
Yield (t/ha)	1.5	2.3	5.6	7.1
Total revenue	1,029.0	1,540.9	865.2	1,110.6
Profit	376.3	917.4	176.6	526.9

These findings align with earlier studies in Zambia and Malawi, which also reported profitability gains from CA due to reduced tillage and input costs (Giller et al., 2011).

eliminated altogether under CA, contributing to overall cost efficiency. Despite a modest increase in seed costs, the yield under CA rises dramatically from 1.5 to 2.3 tons per hectare, resulting in a revenue increase from USD 1,029 to USD 1,540.9. This translates into a profit jump from USD 376.3 under conventional methods to USD 917.4 with CA more than doubling the return.

A similar trend is observed in maize production. CA reduces costs in land preparation, tillage, weeding, and pest control, while slightly increasing expenses in planting and harvesting. Harrowing is again eliminated, reinforcing the cost-saving nature of CA. The yield improves from 5.6 to 7.1 tons per hectare, boosting revenue from USD 865.2 to USD 1,110.6. Consequently, profit margins rose sharply from USD 176.6 to USD 526.9, nearly tripling the returns compared to conventional practices. Thus, CA demonstrates clear advantages in both cost efficiency and productivity. By minimizing unnecessary field operations and optimizing input use, it not only enhances profitability but also supports more sustainable farming systems. These findings strongly advocate for the broader adoption of CA, especially among smallholder farmers seeking to improve yields and income while reducing labor and input costs.

3.4 Challenges of conservation agriculture adoption

The findings reveal a comparative analysis of key agricultural challenges faced by farmers in three villages of Mapogoro, Njelenje, and Muvwa based on responses from 75 participants. Eight major constraints were assessed, with statistical significance evaluated using chi-square tests. Generally, crop-livestock competition emerged as a widespread issue, affecting 80% of respondents, with relatively uniform distribution across villages (72–88%) and no significant inter-village variation $p = 0.368$ (Table 4). However, burning of crop residues and weed problems showed statistically significant differences ($p = 0.028$ and $p = 0.020$, respectively), suggesting localized variations in land management practices and weed pressure. Notably, Njelenje reported the highest incidence of residue burning (84%), while Muvwa had the highest weed-related concerns (76%).

Challenges such as unavailability of marketed produce, high input prices, and lack of capital were consistently reported across villages (68–76%), with no significant differences ($p > 0.5$), indicating systemic constraints in market access and affordability (Table 4). The low level

TABLE 4 Challenges facing farmers in adopting CA practices and technologies.

Challenge	Total, <i>n</i> (%) [*]	Mapogoro, <i>n</i> (%) ^{**}	Njelenje, <i>n</i> (%) ^{**}	Muvwa, <i>n</i> (%) ^{**}	Chi-square	<i>p</i> -value ^{***}
Crop-livestock competition	60 (80)	18 (72)	20 (80)	22 (88)	2.000	0.368
Burning of crop residues	49 (65)	12 (48)	21 (84)	16 (64)	7.182	0.028
Weed problems	40 (53)	11 (44)	10 (40)	19 (76)	7.821	0.020
Unavailability of marketed produce	55 (73)	19 (76)	17 (68)	19 (76)	0.545	0.761
High price of inputs	51 (68)	16 (64)	16 (64)	19 (76)	1.103	0.576
Low level of education	68 (91)	20 (80)	24 (96)	24 (96)	5.042	0.080
Lack of capital	55 (73)	17 (68)	19 (76)	19 (76)	0.545	0.761
Local believes on conservation tillage	31 (41)	3 (12)	11 (44)	17 (68)	16.276	<i>p</i> < 0.0001
Low accessibility of agricultural inputs	45 (60)	13 (52)	15 (60)	17 (68)	1.333	0.513

of education was the most frequently mentioned challenge (91%), though its variation across villages (80–96%) approached statistical significance ($p = 0.080$), potentially reflecting disparities in educational outreach or demographic composition. The most striking inter-village disparity was observed in local beliefs about conservation tillage, with adoption resistance significantly higher in Mapogoro (12%) compared to Muvwa (68%) and Njelenje (44%) ($p < 0.0001$). This suggests that sociocultural perceptions may play a critical role in shaping CA uptake.

Thus, low accessibility to agricultural inputs was reported by 60% of farmers, with moderate variation across villages (52–68%) and no significant difference ($p = 0.513$). Overall, the findings underscore both shared and site-specific constraints in agricultural development, highlighting the need for tailored interventions that address not only technical and economic barriers but also sociocultural dynamics influencing farmer behavior.

4 Conclusion and implications

This study demonstrates that CA practices significantly enhance the climate resilience and economic viability of smallholder farming systems in the Southern Highlands of Tanzania. The integration of minimum tillage, permanent soil cover, and crop rotation not only buffered against climatic extremes such as erratic rainfall and rising temperatures but also improved yields and profitability in maize and beans production. The empirical evidence from both on-station trials and farmer-managed fields confirms that CA is a viable pathway toward sustainable intensification, especially in regions vulnerable to climate variability. Despite widespread adoption of core CA principles like minimum tillage and ox-ripping, barriers such as crop-livestock competition, residue burning, weed pressure, and sociocultural resistance persist. These constraints underscore the need for context-specific interventions that go beyond technical training to include behavioral change, institutional support, and market access. The economic analysis further reveals that CA practices reduce input costs and increase profit margins, making them attractive even for resource-constrained farmers.

Despite the valuable insights generated by this study, several limitations should be acknowledged. First, the research was conducted within a specific agro ecological zone, which may limit the generalizability of findings to other regions with differing soil profiles, rainfall patterns, or socio-economic conditions. Additionally, while the study highlights

short to medium-term agronomic and economic outcomes, it does not capture the long-term effects of the interventions on soil health, carbon dynamics, or resilience to climate variability. The analysis also touches on gender and social inclusion but lacks a fully disaggregated exploration of how intra-household dynamics and cultural norms influence adoption and impact. Furthermore, trade-offs in residue management particularly the tension between soil cover and livestock feed were noted but not quantified, leaving a gap in understanding the broader implications for mixed farming systems. Lastly, while farmer perceptions and adoption trends were considered, the behavioral and institutional factors shaping sustained uptake were not deeply examined.

To address these gaps, future research should pursue longitudinal studies that assess the enduring agronomic and ecological benefits of the CA practices across multiple seasons. Comparative trials across diverse agro ecological zones would help refine recommendations and enhance scalability. There is also a need for more nuanced gender-responsive research that explores decision making, labor dynamics, and benefit distribution within households. Integrating livestock considerations into CA frameworks such as evaluating dual-purpose crops or alternative feed strategies could help resolve residue use conflicts. Moreover, participatory approaches that engage farmers, extension agents, and local institutions in co-designing technologies and training materials may foster more context-relevant and sustainable adoption. Finally, economic modeling under varying market and climate scenarios could offer predictive insights to guide policy and investment decisions. Conservation agriculture enhances productivity, profitability, and resilience among smallholder farmers in Tanzania's Southern Highlands. However, scaling its adoption requires integrated policy support, context-specific training, and access to affordable inputs. Future research should evaluate long-term soil health and carbon sequestration impacts of CA under variable climatic conditions.

5 Study limitations

The geographical focus of the study is on the Southern Highlands of Tanzania, particularly Mbeya region. This region limits the generalizability of results to areas with different soil types, rainfall patterns, cropping calendars and socio-economic contexts. Findings represent short to medium-term outcomes and do not capture multi-year trajectories in soil health, pest and disease dynamics, or the yield persistence and income gains under prolonged climatic stresses. Carbon dynamics and soil health indicators were not measured with the

temporal resolution or depth needed to quantify long-term sequestration, nutrient cycling and structural changes in the soil profile (Dynarski et al., 2020). Trade-offs between maintaining soil cover and needs for livestock feed were identified but not quantified, leaving an incomplete picture of net productivity and livelihood implications in crop–livestock farming systems (Paul et al., 2020). The factors that influence CA adoption such as behavioral, institutional, and intra-household were explored only partially, limiting insight into the social pathways and extension mechanisms required for sustained uptake (Mbagi et al., 2024). Gender equality and dimensions were not fully disaggregated, which limits understanding of how benefits, labor burdens, and access to inputs vary across women, youth, men and other marginalized groups (Lwamba et al., 2022). The economic analysis relied on observed prices and costs from the study period and did not model sensitivity to market volatility, subsidy changes, or long-term price trends, and farmer-managed trials may have been subject to spillovers or unequal resource access that could bias measured treatment effects.

5.1 Directions for future research

The upcoming research should prioritize on longitudinal, multi-season studies that monitor soil organic carbon, aggregate stability, infiltration rates, outbreak of pests and diseases, and yield resilience to establish the durability of CA benefits and discover potential lagged effects. Comparative trials across different agro-ecologies are needed to test transferability, identify context-specific CA packages, and define environmental thresholds for success. Research effort must quantify crop residue allocation decisions and test integrated interventions such as fodder conservation, dual-purpose crops, and feeds processing to resolve conflicts between soil cover and livestock feeds. Integrated livestock–crop studies should evaluate timing and design of tillage adaptations, pasture integration, and nutrient recycling to optimize outcomes for mixed farming systems. Integrated research methods that combines behavioral experiments, social network analysis and institutional assessment will clarify how extension quality, social norms, market linkages, and policy instruments shape CA adoption pathways. Gender-responsive designs must disaggregate outcomes by gender and age to reveal differences in labour, access to tools, decision-making and finance and benefit distribution. Under local management regime, the high-resolution soil sampling and greenhouse gas measurement protocols are required to estimate the net mitigation potential of CA practices and technologies. Economic scenario modeling and sensitivity analysis should evaluate CA performance under alternative market conditions, input supply shocks, subsidy regimes, and climate projections to guide investment and policy. Finally, participatory co-design and scaling experiments that engage farmers, extension agents, and local institutions in iterative testing of CA packages and support mechanisms will accelerate learning and identify viable, context-appropriate pathways for wider CA adoption.

Data availability statement

Data used in this study will be available from the corresponding author upon request.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AK: Conceptualization, Writing – original draft, Data curation, Investigation, Methodology, Validation, Formal analysis, Writing – review & editing, Visualization, Supervision. NM: Writing – original draft, Data curation, Experimental design, Writing – review & editing, Supervision, Investigation, Validation. MM: Writing – original draft, Data curation, Formal analysis, Supervision, Methodology, Writing – review & editing, Validation, Visualization. BMw: Writing – review & editing, Software, Data curation, Visualization. BMv: Writing – review & editing, Methodology, Formal analysis, Data curation, Software, Visualization, Validation. JM: Writing – review & editing, Visualization, Software, Formal analysis, Supervision. RL: Data curation, Visualization, Formal analysis, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The authors express their sincere appreciation to the Tanzania Meteorological Authority for sharing rainfall and temperature data relevant to the study area. They also extend heartfelt thanks to the smallholder farmers in the selected communities for their warm hospitality and valuable contributions.

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.

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