Assessing sustainable intensification options for maize production in smallholder farming systems in Malawi

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Assessing sustainable intensification options for maize production in smallholder farming systems in Malawi

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Abstract

Maize production in Malawi remains constrained by low yields, declining soil fertility, and high climatic variability, necessitating robust sustainable intensification (SI) strategies for smallholder systems. This study evaluated six SI options within a conservation agriculture (CA) framework in Mtunthama Extension Planning Area (EPA), Kasungu District, using on-farm trials established across 44 farms over two consecutive seasons (2023/24 and 2024/25). The treatments included conventional ridge tillage (sole maize), CA sole maize, maize–legume strip intercropping with cowpea (Vigna unguiculata) and lablab (Lablab purpureus), and corresponding maize–legume rotations. Agronomic performance was assessed using maize grain yield, biomass production, and cob number, complemented by farmer preference evaluations.

Results consistently demonstrated the superiority of CA-based maize–legume strip intercropping systems, which achieved higher grain yields (approximately 1.6–1.8 t ha^{-1}), greater biomass production (3.5–5.0 t ha^{-1}), and increased cob numbers relative to sole maize and rotation systems across both seasons. These gains were associated with improved resource-use efficiency arising from complementary interactions in light capture, water use, and nitrogen dynamics, alongside enhanced soil moisture retention and biological nitrogen fixation. In contrast, CA sole maize and conventional systems showed comparatively lower and less stable performance, highlighting that CA alone provides limited short-term yield benefits without crop diversification. Yield improvements observed in the second season further suggest cumulative effects of CA practices on soil structure and nutrient cycling. In addition, legume-integrated systems contributed to the suppression of *Striga asiatica* and increased overall system productivity.

Farmer evaluations strongly aligned with agronomic findings, with maize–cowpea strip intercropping emerging as the most preferred option due to its provision of early-maturing grain, improved moisture retention, and income opportunities. The study demonstrates that integrating legumes within CA systems creates synergistic effects that enhance productivity, resilience, and livelihood outcomes. These findings underscore the importance of systems-based SI approaches that combine conservation agriculture with crop diversification to address both immediate productivity constraints and long-term sustainability in smallholder maize-based systems.

Key words: Conservation Agriculture, intercropping, legume integration, mulch, smallholder farmers, Malawi.

1. Introduction

Maize (*Zea mays* L.) is the cornerstone of food security and rural livelihoods in Malawi, constituting the dominant staple crop and occupying the largest proportion of cultivated land among smallholder farmers in the country (Snapp et al., 2014). Despite its importance, maize productivity remains very low, with an average yield ranging between 1.0 and 2.0 t ha^{-1} which is below the attainable yields under improved management and good rains (Lobell et al.,2009). This persistent yield gap, observed across Malawi and much of sub-Saharan Africa, is driven by a combination of biophysical and agronomic constraints, including declining soil fertility, continuous cereal monocropping, limited organic resource inputs, and increasing rainfall variability (Smale & Jayne, 2010; Chimonyo et al., 2019).

In the Central part of Malawi, particularly in areas such as the Mtunthama Extension Planning Area (EPA) in Kasungu District, maize production is predominantly rain-fed and characterized by smallholder farming systems with limited resource endowment. Fertility management often relies on low and inconsistent mineral fertilizer application, typically without complementary soil amendments. Over time, such practices have resulted in significant depletion of soil organic matter and essential nutrients, especially nitrogen, thereby reducing fertilizer use efficiency and increasing production risks (Vanlauwe et al., 2015). These challenges highlight the urgent need for agronomic approaches that not only improve crop productivity but also restore and sustain the underlying soil resource base.

Sustainable intensification (SI) has emerged as a key framework for addressing this dual challenge of increasing productivity while maintaining environmental sustainability. SI aims to enhance agricultural output from existing farmland while improving resource use efficiency and system resilience (Pretty et al., 2018). In maize-based systems, SI pathways commonly integrate principles of Conservation Agriculture (CA) which includes: minimum soil disturbance, permanent soil cover, and crop diversification (Vanlauwe et al., 2014). Among these, the integration of legumes into maize systems, either through intercropping or rotations, is widely promoted due to its potential to enhance biological nitrogen fixation, improve soil structure, and provide additional benefits such as food, income, and livestock feed (Snapp et al., 2010).

Practical evidence from sub-Saharan Africa indicates that maize–legume systems can significantly improve productivity and system stability. For example, maize grown after legumes has been shown to yield 30–50% more than continuous maize systems (Snapp et al., 2010), while CA practices can improve soil moisture retention and soil organic carbon over time (Thierfelder & Wall, 2010). However, the performance of these SI options is highly context-specific, influenced by local variations in soil type, initial fertility status, rainfall patterns, and management practices such as residue retention and mulch cover (Steward et al., 2015; Chimonyo et al., 2019). This variability underscores the need for site-specific, on-farm evaluations that capture real-world conditions and farmer management practices.

Beyond agronomic performance, farmer preferences and perceptions are critical for the successful adoption of SI options. Smallholder farmers often prioritize technologies that address immediate needs, including food security, income generation, and resilience to climate variability. For instance, early-maturing legumes such as cowpea (*Vigna unguiculata*) and lablab (*Lablab purpureus*) can provide grain for consumption and sale within a shorter growing period, thereby enhancing household nutrition and income while also contributing to soil fertility improvement. Understanding these preferences is therefore essential for identifying SI options that are both agronomically effective and socially acceptable.

Against this background, this study aimed to assess the performance of selected sustainable intensification options for maize production under smallholder farming conditions in Malawi at

Mtunthama EPA. Specifically, the study evaluates conservation agriculture-based systems which incorporate maize–legume strip intercropping and rotations with cowpea and lablab, in comparison with conventional tillage system. Using data from 44 on-farm trials conducted over two consecutive seasons (2023/24 and 2024/25) in Mtunthama EPA, the study quantifies differences in maize and legume grain yield, biomass production, and yield components (number of cobs per net plot). In addition, it examines how treatment performance is influenced by seasonal variation, initial soil conditions, and management factors such as mulch cover. By integrating agronomic measurements with farmer evaluations from field days, the study provides a comprehensive, context-specific assessment of SI options and their potential to enhance productivity, resilience, and livelihoods in smallholder maize-based systems.

2.0 Methodology

2.1 Study Area Description

The study was conducted in Kasungu District, located on the Central Region plateau of Malawi (Figure 2.1). The district experiences three distinct seasons: a cool dry winter (May–August) with mean monthly temperatures ranging from 17–27 °C, a hot dry season (September–October), and a rainy season (November–April) characterised by monthly temperatures between 25–37 °C. Annual rainfall averages between 800 and 1000 mm, although local variability occurs due to topographic heterogeneity (Chimonyo et al., 2023).

Soils in Kasungu are predominantly medium-textured sandy loams, generally characterised by low organic matter and high susceptibility to nutrient depletion under continuous cultivation. Patches of clay loam soils occur in selected areas and are typically preferred for cropping. Soil erosion rates have increased over recent decades, indicating declining soil fertility and structural stability (Mvula, 2017). Maize is the dominant staple crop and occupies the majority of cultivated land annually, often intercropped with legumes such as soybean, cowpea, and groundnut (Ngwira et al., 2013; Chimonyo et al., 2023).

These agro-ecological characteristics, combined with variability in rainfall distribution and soil fertility, provide a suitable context for evaluating the agronomic performance of sustainable intensification practices at plot level. The spatial distribution of the 44 experimental plots established within Mtunthama EPA of the district is illustrated in Figure 2. This map is used to contextualise environmental heterogeneity rather than to infer farm-level differences.

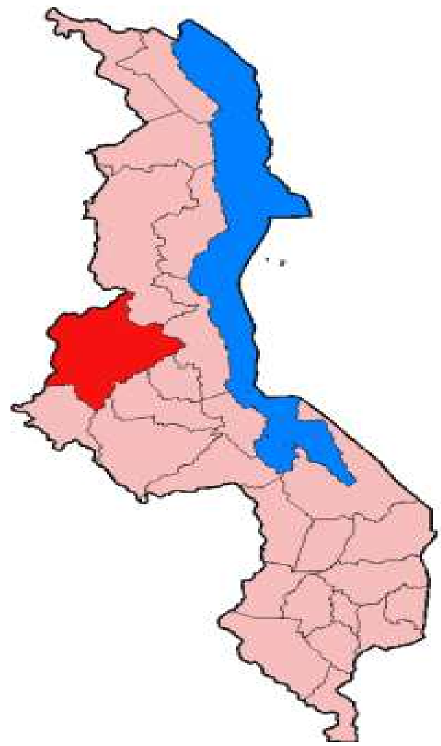

Figure 1: Map of Malawi with the Kasungu district indicated in red, and lake Malawi indicated in blue (Wikipedia, 2022)

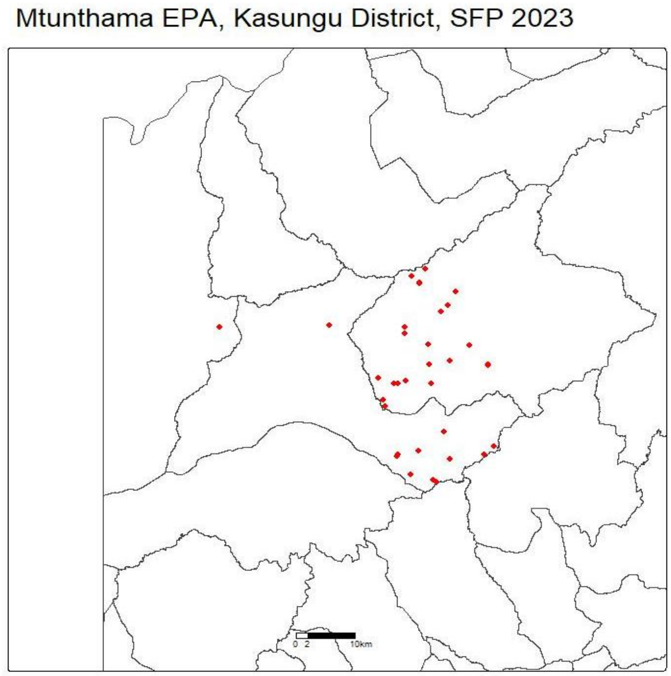

Figure 2: Map of Mtunthama EPA showing farm locations marked in red dots

2.2 Experimental Design and Treatment Setup

An on-farm experimental design was employed to evaluate sustainable intensification (SI) options for maize production under real field conditions across two consecutive agricultural seasons (2023/24 and 2024/25). Full treatment sets were established on 44 farms in Mtunthama EPA, with each farm containing all six treatments to ensure direct comparability within sites while capturing environmental variability across the landscape. Plot sizes were standardised at 25 m × 15 m for maize-based plots and 12.5 m × 7.5 m for legume plots, with consistent treatment allocation across both seasons.

The trial was designed to assess progressively complex SI strategies. In the first season, treatments focused on comparing conventional maize with Conservation Agriculture (CA)-based systems incorporating legume intercropping and residue retention. In the second season, the design was expanded to include maize grown in rotation with the legume species tested in the first season, allowing comparison of intercropping versus rotation effects within a CA framework.

The six agronomic treatments, with their corresponding plot identifiers and core features, are summarised in Table 1, followed by Table 2, which presents the field layout.

Table i: Description of agronomic treatments and plot layout implemented in the on-farm trials, Mtunthama EPA, Malawi.

Treatment Type	Crops	Plot Number	Description
Conventional Maize	Maize	Plot 1	Maize planted with ridges (traditional practice).
CA Maize	Mazie	Plot 2	Maize planted without ridges. 1. Includes mulching *(20 plots out of 44 received mulch)*
CA Maize intercropping	Cowpea Maize	Plot 3	Maize intercropped with inoculated cowpea (double-row strip cropping). 2. Includes mulching *(25 plots out of 44 received mulch)* 3. Crop diversification
CA Maize intercropping	Lablab Maize	Plot 4	Maize intercropped with inoculated lablab (double-row strip cropping). 4. Includes mulching *(19 plots out of 44 received mulch)* 5. Crop diversification
CA Maize rotation	Cowpea Maize	Plot 5a Plot 5b	Rotation between maize and inoculated cowpea. In Year 1, regarded as sole maize and sole cowpea due to lack of prior rotation data. 6. Includes mulching *(15 plots out of 44 received mulch)*

CA Maize rotation	Lablab	Plot 6a	Rotation between maize and inoculated lablab. In Year 1, regarded as sole maize and sole lablab due to lack of prior rotation data.
	Maize	Plot 6b	
			7. Includes mulching
			(13 plots out of 44 received mulch)

Table ii: Field layout

15 m	15 m	15 m		
Plot 1. Conventional ridging with continuous sole maize	Plot 3. CA with maize/inoculated cowpea double-row strip cropping	Plot 5a. CA with inoculated cowpea-maize rotation	Plot 5b. CA with maize-inoculated cowpea rotation	25 m
Plot 2. CA with continuous sole maize	Plot 4. CA with maize/inoculated lablab double-row strip cropping	Plot 6a. CA with inoculated lablab-maize rotation	Plot 6b. CA with maize-inoculated lablab rotation	25 m

Data collection focused on plot-level agronomic parameters. In both seasons, core measurements included plant stand counts, cob counts, and grain yield determined from a standardised net harvest area (5 m × two central rows), shelled, weighed, and corrected to 12.5% moisture content. In the 2024/25 season, additional variables were incorporated, including total fresh biomass weight, subsample collection for dry matter calibration, and counts of the parasitic weed *Striga asiatica*.

2.3 Farmer Selection Trial Management and Agronomic Practices

Farmers were selected in collaboration with local extension officers based on interest and land availability to host the full experimental layout. From an initial list of 50 randomly chosen farmers, five withdrew due to labour constraints or changes in cropping intentions, resulting in 45 participating farms. Selected farmers received standardised inputs (maize, cowpea, and lablab seeds; fertilisers; pesticides) and participated in group training on plot layout, planting procedures, and treatment-specific protocols, including residue retention and the required 75 cm row spacing for maize-legume systems.

All crops were planted following the first effective rains after 15 December in both seasons. Maize (variety MH43), cowpea (variety Sudan), and lablab (variety Hayworth) were used. For sole crops, row spacing was standardised at 75 cm for maize and 60 cm for legumes, with in-row spacing of 25 cm and 20 cm, respectively. In intercrop treatments (Plots 3 & 4), the maize population was maintained by planting two rows of maize 50 cm apart, alternating with two rows of legumes spaced at 45 cm. A uniform fertiliser regime was applied to all maize plots: a basal application of 100 kg ha^{-1} of NPK fertiliser at planting, followed by a top-dressing of 100 kg ha^{-1} of urea. Pre-emergence weed control was achieved with a blanket application of glyphosate at a rate of 2.5 L ha^{-1}. Mulch coverage, defined as the percentage of ground covered by retained crop residues, was quantified in each plot and recorded as a continuous variable for use as a covariate in statistical models to account for within-treatment variability.

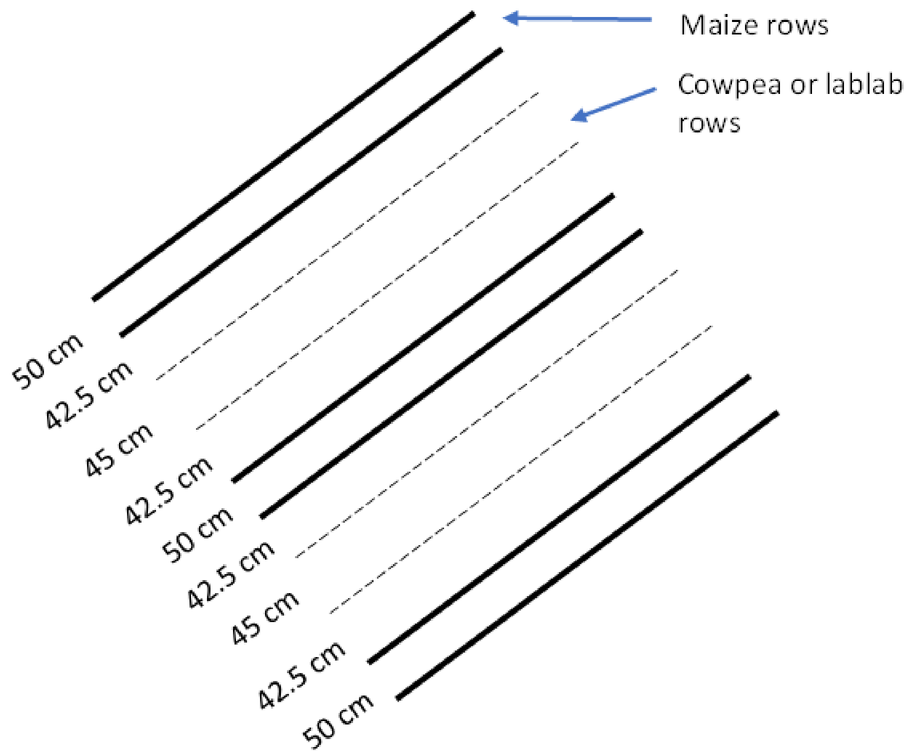

Figure 3: A schematic illustration of planting configuration for double-row strip cropping for maize and cowpea or lablab in Treatments 3 and 4.

2.4 Harvesting, Yield Measurement, and Yield Components

The primary agronomic response variable was maize grain yield (kg ha^{-1}). Yield was determined from a standardized net harvest area of 5 m length encompassing two central crop rows. All cobs within this area were harvested, sun-dried, shelled, and weighed using a calibrated digital scale (±5 g precision). Grain weight was adjusted to a standard moisture content of 12.5%. For legume intercrops and rotation plots, all mature pods within an equivalent net plot area were harvested sequentially at maturity, air-dried, threshed, weighed, and adjusted to 12% moisture.

Seed moisture content (SMC) at harvest was determined on a wet weight basis using six randomly selected ears per plot, calculated as:

$$SMC = \frac{M1 - M2}{M1} \times 100$$

where M1 is the fresh mass (g) and M2 is the dry mass (g) of seeds. Thousand-seed weight (TSW) was determined by counting 100 seeds and multiplying by 10.

Additional yield components recorded at plot level included plant population per hectare, extrapolated from plant counts within the harvest area, number of cobs per plant, shelling percentage, calculated as the ratio of grain weight to total cob weight, and above-ground biomass yield, estimated from dry stover weight and converted to per-hectare basis

In the 2024/25 season, protocol enhancements included recording total fresh biomass weight and collecting subsamples (nine representative maize cobs per plot; approximately 3 kg of legume pods) for precise dry matter calibration. Dry matter content for grain and biomass fractions was used to adjust total plot weights. *Striga asiatica*counts were also conducted within the net harvest area as an indicator of parasitic weed pressure.

2.5 Soil sampling and baseline characterization

Prior to trial establishment, composite soil samples were collected from each experimental plot at a depth of 0–20 cm to establish baseline soil fertility conditions. Samples were air-dried, ground, and sieved through a 2 mm mesh before laboratory analysis. The analytical procedures included soil pH (water method), organic carbon (Walkley–Black method), total nitrogen (Kjeldahl method), available phosphorus (Bray-1 method), and exchangeable bases (K, Ca, Mg). These measurements provided baseline soil property data for each plot.

2.6 Statistical Analysis

Statistical analysis was performed using R software and emphasised direct, plot-level comparisons of agronomic performance. Descriptive statistics (mean, median, standard deviation, range) were calculated for maize grain yield and key covariates (mulch cover %, baseline soil properties) by treatment.

2.7 Farmer Perception and Innovation Scoring

To contextualise the agronomic results, participatory field days were held at two trial sites following the seasonal harvests. These events facilitated direct observation of the treatments. A structured voting exercise was conducted where attending farmers selected their top three preferred management practices based on in-field observation. Ballots were collected separately from men and women to allow for gender-disaggregated analysis of preferences. Different treatments were qualitatively evaluated by the farmers present and other invited stakeholders. To quantify these perceptions, farmers were also asked to individually score each treatment on a numeric scale based on criteria such as perceived yield benefit and labour demand. These scores were compiled to provide a supplementary perspective to the agronomic data.

2.8 Declarations

2.8.1 Clinical trial registration

Clinical trial registration: Not applicable.

2.8.2 Consent to Publish

Consent to Publish: Not applicable.

2.8.3 Consent to Participate

Informed consent was obtained from all individual participants involved in the study prior to data collection.

2.8.4 Ethics declaration

The study involved voluntary participation of smallholder farmers in household surveys, focus group discussions, and participatory evaluations. Informed consent was obtained from all participants prior to data collection, and participants were assured of confidentiality and anonymity of the information provided.

2.8.5 Plant Ethics

This study involved on-farm agronomic field experiments and it did not involve the collection of wild plant species, endangered species, protected species, or herbarium specimens. The crop species used in the experiments included maize (*Zea mays* L.), soybean (*Glycine max* L.), cowpea (*Vigna unguiculata* L.), lablab (*Lablab purpureus* L.) and pigeon pea (*Cajanus cajan* L.). The study made use of cultivated varieties obtained through the International Maize and Wheat Improvement Center (CIMMYT), the Department of Agricultural Research Services (DARS), Malawi, and collaborating agricultural research programs.

Crops identification and verification were conducted by qualified agronomists and researchers from the Department of Agricultural Research Services (DARS), Malawi, and CIMMYT

Malawi, who routinely manage and evaluate these crop species within national agricultural research programs.

The experiments were established on voluntarily provided farmland belonging to participating smallholder farmers. Permission to conduct the study was obtained from the participating farmers, local community leaders, and the relevant agricultural authorities within Kasungu District and Mtunthama EPA before implementation.

All crops used in this study complied with national agricultural research regulations and guidelines in Malawi. No permits or licenses were required because the study involved cultivated crop species used under normal agricultural research and extension activities.

2.8.6 Plant Materials

The study evaluated maize-based sustainable intensification technologies involving maize, soybean, cowpea, lablab, pigeon pea. Seed for the experimental crops was obtained from the International Maize and Wheat Improvement Center (CIMMYT), Malawi, and the Department of Agricultural Research Services (DARS), Malawi. The experiments were conducted in farmers' fields located in Mtunthama EPA, Kasungu District, Malawi. All crop species used were cultivated agricultural crops commonly grown in Malawi and were not collected from natural habitats.

2.8.7. Data Availability Statement

The datasets generated and analyzed during our study are not publicly available because they contain information obtained from participating farming households and are subject to confidentiality agreements. However, anonymized data supporting the findings of this study are available from the corresponding author upon reasonable request.

2.8.9 Funding

This research was initiated under the Sustainable Intensification of Mixed Farming Systems (SIMFS) project coordinated by International Maize and Wheat Improvement Center. Initial field activities were supported during the first season of project implementation. However, following premature discontinuation of project funding associated with the United States government funding cuts and Trump administration directives affecting international development programs, additional data collection and completion of the study were largely financed by the corresponding author using personal resources.

1. Results

3.1 Weather Data During the Study Seasons

Weather data indicated moderate differences in both rainfall distribution and temperature conditions between the 2023/24 and 2024/25 maize growing seasons (November–April) in Kasungu District. Overall, both seasons followed the district's typical unimodal rainfall regime, but variations were evident in onset timing, cumulative rainfall totals, and mid-season precipitation intensity. Statistical analysis confirmed that the inter-annual temperature differences were not significant ($F = 0.32$, $p = 0.73$).

Table iii: Monthly rainfall totals for the 2023/24 and 2024/25 seasons (Malawi Department of Climate Change and Meteorological Services)

Season	Nov	Dec	Jan	Feb	Mar	Apr	Total
2023/24	79.5	82.2	237.9	207.9	84.4	8.4	**700.3**
2024/25	42.3	100.3	217.7	125.9	96.6	19.2	**602.0**

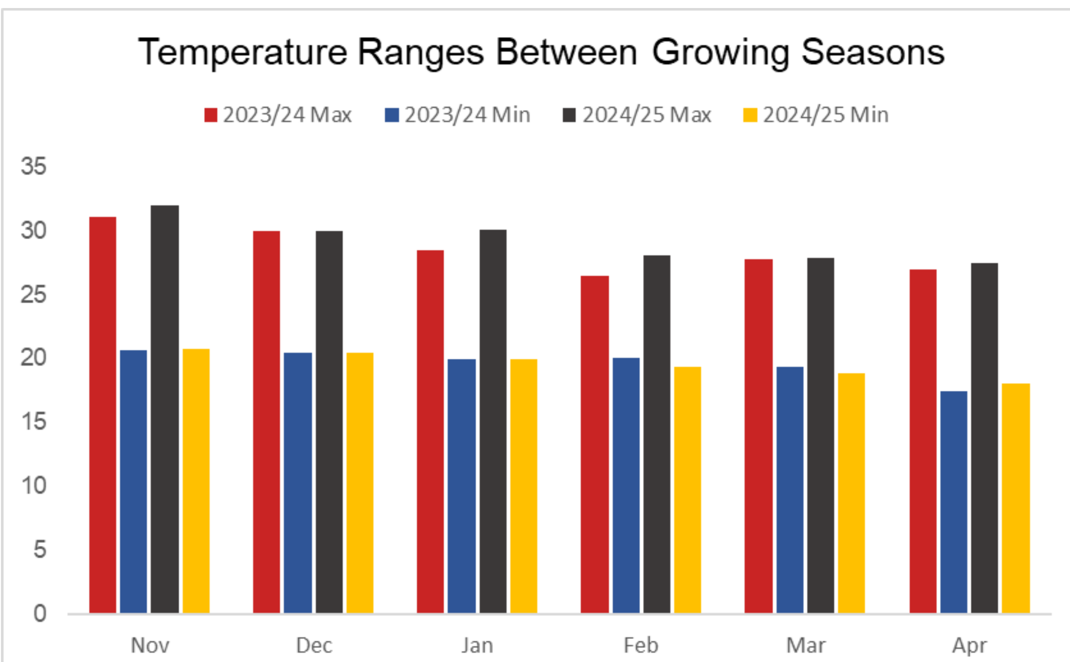

Figure 4:Temperature for growing months of Maize

3.2 Preliminary soil fertility analysis

Baseline soil analysis across all experimental plots indicated moderately acidic to near-neutral conditions, with mean pH of 6.05 (Figure 5). Soil organic carbon averaged 1.11%, corresponding to organic matter content of 1.92%. Mean total nitrogen was 0.10%, reflecting limited inherent nitrogen reserves typical of continuously cultivated smallholder systems. Available phosphorus averaged 30.50 µg g^{-1}, while exchangeable potassium, calcium, and magnesium averaged 0.31 cmol kg^{-1}, 3.71 cmol kg^{-1}, and 0.39 cmol kg^{-1}, respectively. These baseline characteristics provide context for interpreting plot-level yield responses to the different sustainable intensification options.

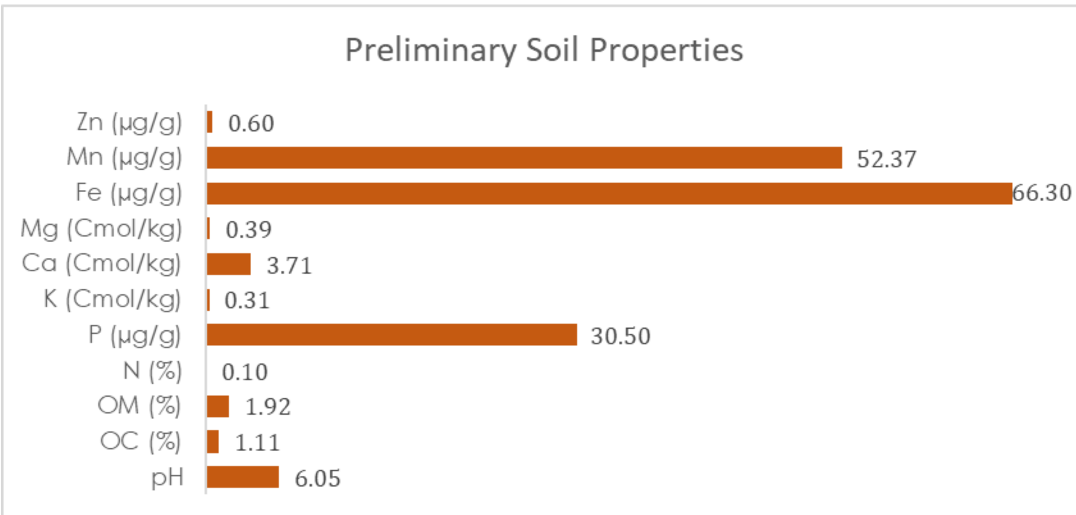

Figure 5: Soil properties for Mtunthama EPA

3.3 Number of Maize cobs per net plot

The number of maize cobs per net plot is one of the key yield-determining components. As shown in Figure 7, cob numbers varied across treatments and between seasons, with clear differences in central tendency and distribution.

In 2024, higher cob numbers were generally observed under the strip-cropping systems compared to other treatments. Both CA maize–cowpea strip cropping and CA maize–lablab strip cropping exhibited relatively higher median values (around 40 cobs per net plot), with upper quartiles extending beyond 45 cobs, indicating comparatively stronger performance. Rotation systems showed intermediate cob numbers, with CA maize–lablab rotation slightly outperforming CA maize–cowpea rotation, although both remained below the strip systems in terms of median values. Lower cob numbers were recorded under CA sole maize and conventional maize, with conventional maize showing one of the lowest medians.

In 2025, an overall increase in cob numbers was observed across most treatments. The CA maize–cowpea strip system showed a noticeable rise in median cob count to the mid-40s, with the upper range exceeding 50 cobs per net plot. Similar improvements were observed for CA maize–lablab strip and CA maize–lablab rotation treatments, which displayed relatively higher medians compared to other treatments. Rotation systems continued to exhibit intermediate performance, while CA sole maize and conventional maize maintained comparatively lower median cob numbers, although slight increases were evident relative to 2024.

Across both seasons, substantial variability within treatments was observed, as indicated by the wide interquartile ranges and the presence of numerous outliers. In some cases, cob numbers extended beyond 50 cobs per net plot, particularly in 2025. Generally, there was general increase in cob number in 2025 relative to 2024 across most treatments. However, considerable variability was observed within treatments, as indicated by the spread of the boxplots and the presence of outliers, suggesting variability in field conditions and management practices.

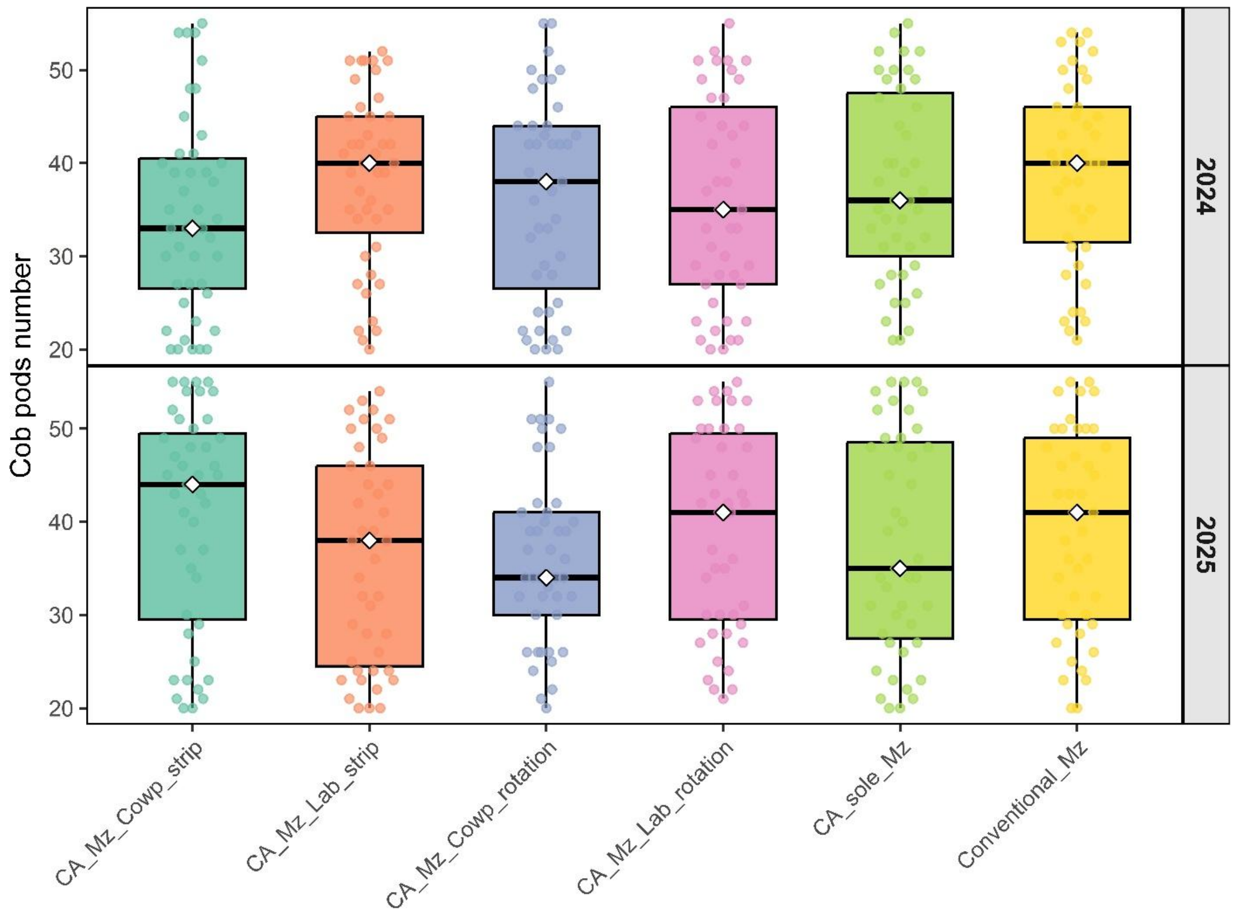

Figure 6: Number of maize cobs per net plot under six management treatments: conservation agriculture maize–cowpea strip cropping, conservation agriculture maize–lablab strip cropping, conservation agriculture maize–cowpea rotation, conservation agriculture maize–lablab rotation, conservation agriculture sole maize, and conventional sole maize, across the 2024 and 2025 growing seasons in Mtunthama Extension Planning Area. Boxplots represent the median, interquartile range, and variability across plots.

3.4 Maize yield distribution by treatment

Maize grain yield, the primary agronomic response variable, varied across the six treatments and between the two growing seasons (Figure 7; Appendix 1). The boxplots illustrate clear differences in yield distribution, central tendency, and variability among treatments.

In 2024, the highest grain yields were observed under the maize–legume strip-cropping systems. Both CA maize–cowpea strip and CA maize–lablab strip treatments exhibited relatively higher median yields (approximately 1,500–1,600 kg ha^{-1}), with upper ranges extending beyond 2,500 kg ha^{-1} in some plots. Rotation systems showed intermediate performance, with CA maize–lablab rotation having slightly higher median yields than CA maize–cowpea rotation. Lower median yields were recorded under CA sole maize and conventional maize, with conventional maize generally among the lowest-performing treatments.

In 2025, yield distributions shifted upward for several treatments. The CA maize–cowpea strip and CA maize–lablab strip systems maintained relatively higher median yields (around 1,700–1,800 kg ha^{-1}), with some observations exceeding 3,000 kg ha^{-1}. Rotation systems continued to show intermediate yields, while CA sole maize and conventional maize remained comparatively lower, although slight improvements were evident relative to 2024.

Across both seasons, strip-cropping systems consistently showed higher median yields compared to rotations and sole maize systems. Rotation treatments maintained moderate performance, while sole maize systems, particularly conventional maize, tended to record lower yields. Variability within treatments was substantial, as indicated by wide interquartile ranges and the presence of numerous outliers, reflecting heterogeneity in field conditions and management practices.

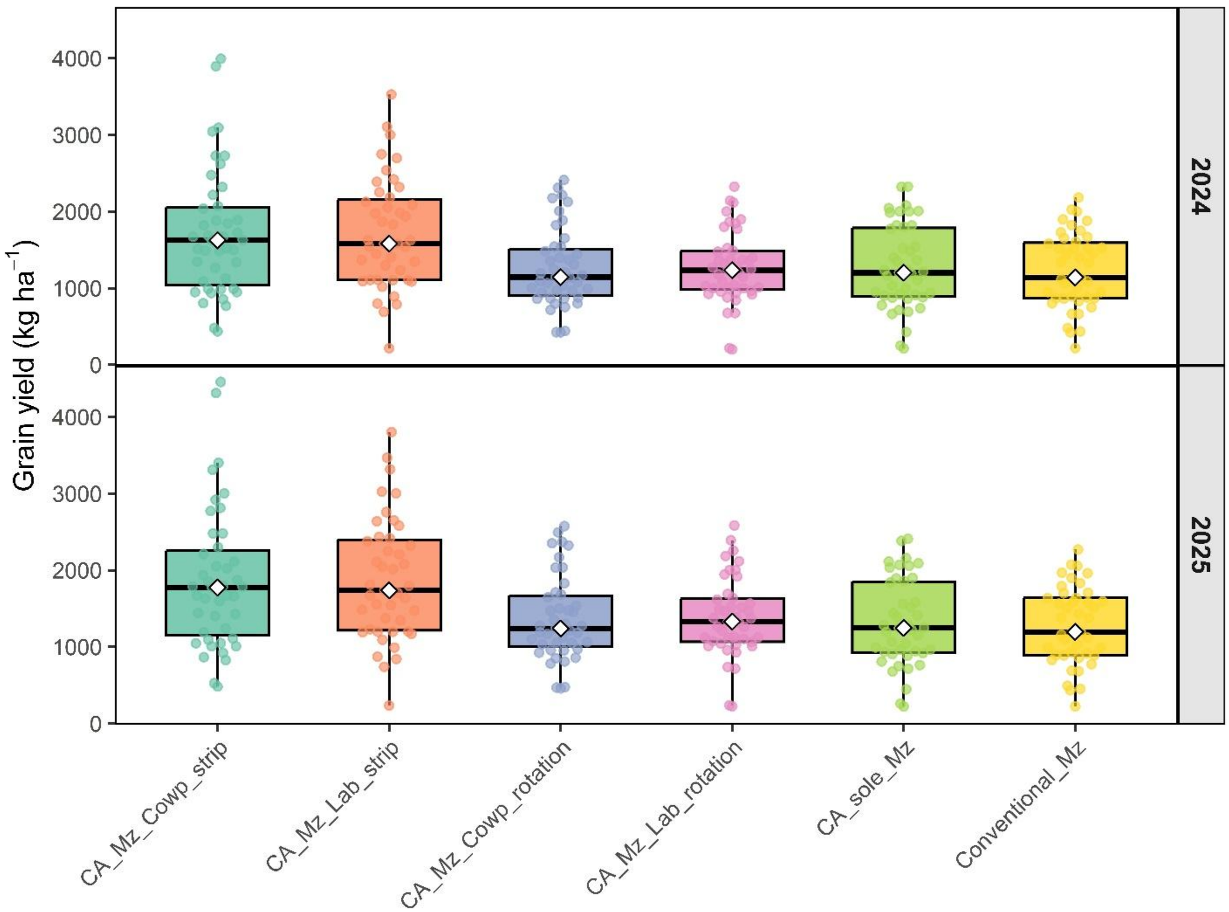

Figure 7: Boxplot of maize grain yield (kg/ha) across six treatment types: conservation agriculture maize–cowpea strip cropping, conservation agriculture maize–lablab strip cropping, conservation agriculture maize–cowpea rotation, conservation agriculture maize–lablab rotation, conservation agriculture sole maize, and conventional sole maize, across the 2024 and 2025 seasons in Mtunthama Extension Planning Area. Boxplots represent median, interquartile range, and variability across plots.

3.5 Biomass performance across treatments

Maize biomass yield, an important indicator of both crop productivity and residue availability, varied across treatments and between seasons (Figure 8; Appendix 2). The boxplots show clear differences in biomass distribution, central tendency, and variability among treatments.

In 2024, biomass yields were relatively higher under the conservation agriculture (CA)-based systems compared to conventional maize. The strip-cropping treatments (CA maize–cowpea strip and CA maize–lablab strip) exhibited comparatively high median biomass values (approximately

3,500–3,700 kg ha^{-1}), with upper ranges extending beyond 4,000 kg ha^{-1}. Rotation systems (CA maize–cowpea rotation and CA maize–lablab rotation) also showed relatively strong performance, with median values comparable to, and in some cases slightly exceeding, those of the strip systems. In contrast, lower biomass yields were observed under CA sole maize and conventional maize, both showing medians around 3,100–3,300 kg ha^{-1}.

In 2025, biomass yields increased across most treatments. The CA maize–lablab rotation and CA maize–lablab strip systems showed relatively higher median biomass values (approaching or exceeding 4,800–5,000 kg ha^{-1}), followed closely by CA maize–cowpea strip and CA maize–cowpea rotation. The strip and rotation systems generally exhibited higher upper ranges, with several observations exceeding 5,500 kg ha^{-1}. CA sole maize and conventional maize continued to record comparatively lower biomass yields, with medians around 3,300–3,600 kg ha^{-1}, although slight improvements were evident compared to 2024.

Across both seasons, CA-based systems (strip-cropping and rotations) consistently showed higher biomass yields relative to sole maize systems, while conventional maize remained among the lowest-performing treatments. Substantial variability within treatments was evident, as indicated by wide interquartile ranges and the presence of outliers, reflecting heterogeneity in field conditions and management practices.

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Figure 8: Biomass yield (kg ha^{-1}) of maize under six management treatments: conservation agriculture maize–cowpea strip cropping, conservation agriculture maize–lablab strip cropping, conservation agriculture maize–cowpea rotation, conservation agriculture maize–lablab rotation, conservation agriculture sole maize, and conventional sole maize, across the 2024 and 2025 seasons in Mtunthama Extension Planning Area. Boxplots represent median, interquartile range, and variability across plots.

3.6 Farmer Perceptions and Innovation Preferences

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A total of 758 farmers participated in field day evaluations across two sites (398 at Sarai Mkanase's farm; 360 at Charles Kanyenda's farm), with balanced gender representation (358 male, 400 female voters). Farmers selected their top three preferred innovations from the trial plots through a structured voting exercise, with results disaggregated by gender and site (Table 6).

The maize-cowpea strip intercrop (Plot 3) emerged as the most preferred innovation, receiving 91 votes across both sites and gender. This was followed by soybean grown with organic inputs and inoculant (Plot 8A) with 62 votes. Two rotation systems, maize-cowpea rotation with maize first (Plot 5B) and maize-lablab rotation with maize first (Plot 6B), each received 58 votes, ranking third.

Gender-disaggregated results showed that both men and women strongly favoured intercrops and rotations, though some site-specific differences were observed. Women at Sarai tended to cast more votes for intercrops, while men at Charles expressed greater interest in soybean under improved management.

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Host farmer explaining the overview of the trial to participants during the field day exercise, highlighting the objectives, management practices, and key observations from the trials

Table iv: Field Day Voting Results – Summary of Farmer Preferences by Site and Gender

Plot	Innovation	Sarai Male	– Sarai Female	– Charles Male	– Charles Female	– Combined Total
Plot 1	Conventional maize (sole)	12	27	15	2	56
Plot 2	CA sole maize	30	15	12	20	77
Plot 3	Maize–Cowpea intercrop (strip)	48	103	29	54	234
Plot 4	Maize–Lablab intercrop (strip)	40	29	24	58	151
Plot 5A	Cowpea–Maize rotation (cowpea first)	14	17	19	11	61
Plot 5B	Maize–Cowpea rotation (maize first)	11	16	21	20	68
Plot 6A	Lablab–Maize rotation (lablab first)	19	18	4	12	53
Plot 6B	Maize–Lablab rotation (maize first)	10	8	25	15	58

4.0 Discussion

The results of this study demonstrate that sustainable intensification options integrating legumes within conservation agriculture (CA) systems significantly enhance maize productivity under smallholder conditions in Mtunthama Extension Planning Area. In particular, maize–legume strip intercropping systems consistently outperformed sole maize and rotation systems in terms of grain yield, biomass production, and cob number per net plot. These findings align with a growing body of evidence indicating that cereal–legume intercropping systems improve productivity through enhanced resource-use efficiency and ecological complementarities (Snapp et al., 2010; Iqbal et al., 2019), with broader system-level evidence supporting these gains across diverse agroecosystems (Abdul Rahman et al., 2021).

The superior performance of strip intercropping systems can be attributed to complementary interactions between maize and legumes in the use of key growth-limiting resources, including light, water, and nutrients. In such systems, maize, as the dominant crop, captures a greater proportion of incident radiation, while legumes occupy lower canopy layers, improving canopy stratification and photosynthetically active radiation (PAR) use efficiency (Iqbal et al., 2019). This spatial and temporal complementarity enhances total system photosynthesis and biomass accumulation. Moreover, intercropping modifies the field microclimate, particularly temperature, humidity, and light distribution, which has been shown to improve crop physiological performance and growth (Iqbal et al., 2019). These mechanisms collectively explain the observed increases in biomass and grain yield under strip intercropping systems.

Nitrogen dynamics also play a central role in driving productivity gains in legume-integrated systems. Legumes contribute to biological nitrogen fixation, increasing nitrogen availability within the system while reducing losses associated with leaching and volatilization. This enhanced nitrogen supply supports improved maize growth, as nitrogen is a critical determinant of key physiological processes such as leaf area development, chlorophyll content, and photosynthetic capacity. Experimental evidence shows that enhanced nitrogen availability supports key physiological processes such as leaf development and grain formation (Ashraf et al., 2016), which are widely associated with improved yield components in maize-based systems. The higher cob number observed in this study under strip intercropping systems is therefore indicative of improved reproductive development driven by enhanced nutrient availability and overall plant vigor.

Biomass production followed trends similar to grain yield, with intercropping systems producing substantially higher biomass than sole cropping systems. This is particularly important in smallholder farming systems, where crop residues serve multiple functions, including soil cover, organic matter inputs, and livestock feed. Increased biomass under CA-based intercropping systems suggests improved photosynthetic efficiency and resource capture. However, the role of biomass extends beyond productivity gains; it is central to broader system sustainability. In mixed crop–livestock systems, crop residues are often preferentially allocated to livestock feed, potentially limiting their contribution to soil fertility. Evidence from Eastern Africa indicates that as productivity increases, farmers may reallocate biomass between soil cover and livestock feed depending on system priorities (Duncan et al., 2016). This highlights the importance of considering biomass not only as an output but also as a critical component of system-level trade-offs and decision-making.

The moderate performance of maize–legume rotation systems observed in this study suggests that while rotations contribute to soil fertility improvement, their benefits may not be immediately realized. Unlike intercropping, which allows simultaneous resource sharing and complementarity, rotational systems rely on residual effects that accumulate over time. This finding is consistent with previous studies indicating that the benefits often accrue gradually and are strongly influenced by residue management and baseline soil fertility conditions (Franke et al., 2018). In contrast, intercropping provides more immediate productivity gains due to concurrent interactions between component crops.

Seasonal variation also influenced treatment performance, with slightly higher yields, biomass, and cob numbers recorded in the second season. This pattern suggests cumulative benefits associated with CA practices, particularly improvements in soil structure, moisture retention, and nutrient cycling over time. Conservation agriculture systems are known to exhibit progressive improvements in soil structure, moisture retention, and yield stability over time (Thierfelder et al., 2015). Furthermore, the observed seasonal differences may reflect variability in rainfall distribution, which plays a critical role in determining crop performance. Intercropping systems are particularly advantageous under such conditions, as they enhance resilience by spreading production risk across multiple crops. Studies have shown that in seasons with lower maize yields, legume yields may compensate, thereby stabilizing overall system productivity (Abdul Rahman et al., 2021).

An important dimension of intercropping systems is their efficiency in land use. Although Land Equivalent Ratio (LER) was not explicitly calculated in this study, the observed yield advantages are consistent with findings from similar systems where LER values greater than one indicate superior land productivity compared to monocropping. In some cases, LER values greater than one are commonly reported, indicating higher land-use efficiency relative to monocropping systems (Iqbal et al., 2019; Abdul Rahman et al., 2021). This underscores the potential of strip intercropping as a viable strategy for intensifying production in land-constrained smallholder systems.

In addition to productivity gains, this study observed that legume-integrated systems contributed to the suppression of *Striga asiatica*, a major biotic constraint to maize production in sub-Saharan Africa. The reduction in Striga infestation under intercropping systems can be attributed to multiple interacting factors, including improved soil fertility, enhanced crop vigor, shading effects, and the presence of mulch under CA practices. Improved soil fertility and crop vigor reduce the production of germination stimulants required for Striga emergence, while increased canopy shading further suppresses its development. These findings are consistent with previous studies demonstrating that integrated soil fertility management and organic matter inputs can significantly reduce Striga incidence (Carsky et al., 2000).

The performance of legumes within intercropping systems further highlights the multifunctional benefits of diversification. Both cowpea and lablab produced higher yields under strip intercropping compared to other treatments, indicating that these systems enhance not only maize productivity but also legume performance. This is particularly important for smallholder farmers, as legumes provide early maturing grain for household consumption and income generation, thereby improving food security and livelihood resilience. Moreover, diversified systems have been shown to increase economic returns and reduce income variability, making them more attractive to risk-averse farmers (Pretty et al., 2018; Abdul Rahman et al., 2021).

Farmer perceptions strongly reinforced the agronomic findings of this study. The preference for maize–cowpea strip intercropping reflects its ability to meet multiple farmer objectives, including improved moisture availability, early food supply, and income generation. The introduction of new legume varieties further suggests potential for adoption and scaling, particularly when technologies deliver immediate and tangible benefits. This observation is consistent with evidence that smallholder adoption is driven by technologies that provide immediate, low-risk benefits aligned with household needs (Smale & Jayne, 2010).

Overall, this study demonstrates that the integration of legumes within CA systems creates synergistic effects that enhance productivity, resource-use efficiency, and system resilience. While conservation agriculture alone may provide limited short-term benefits, its combination with legumes addresses key soil fertility constraints and improves system performance. Beyond confirming existing knowledge, these findings contribute to a deeper understanding of sustainable intensification by highlighting the role of intercropping as a mechanism for optimizing resource complementarities, reducing production risks, and enhancing multifunctionality in smallholder farming systems. This supports the argument that sustainable intensification strategies must move beyond single interventions and instead adopt integrated approaches that simultaneously address productivity, resilience, and sustainability objectives (Vanlauwe et al., 2014).

5.0 Conclusion

This study demonstrates that maize–legume strip intercropping within conservation agriculture (CA) systems is a highly effective pathway for sustainable intensification in smallholder farming systems of central Malawi. The consistent increases in grain yield, biomass, and cob number observed under intercropping systems reflect improved resource-use efficiency driven by complementary interactions in light capture, water use, and nitrogen dynamics. Legume integration enhanced biological nitrogen fixation and soil fertility, which in turn supported better crop growth, photosynthetic performance, and reproductive development. These findings indicate that the productivity gains were not only a result of improved soil conditions but also of underlying physiological and ecological mechanisms that optimize system performance.

Beyond yield improvements, the integration of legumes contributed to the suppression of *Striga asiatica*, increased system resilience to seasonal variability, and enhanced overall productivity, including higher legume yields. The multifunctional benefits of intercropping, ranging from soil fertility improvement to risk reduction and diversified outputs, were further reinforced by strong farmer preference, particularly for maize–cowpea systems that provide early food and income. Overall, the study confirms that sustainable intensification in maize-based systems is best achieved through integrated, systems-based approaches that combine CA with legume diversification, enabling simultaneous gains in productivity, resilience, and livelihood outcomes.

Declaration of Competing Interest

This manuscript is original unpublished work, read and approved by all authors, and not being considered for publication elsewhere. All those listed as authors have contributed to the development of this paper and have approved the manuscript and this submission. We have no conflicts of interest to declare.

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References

Abdul Rahman, M., Zhang, J., Rahman, M. H., & Wang, X. (2021). Intercropping systems and resource-use efficiency: A global review. Agricultural Systems, 190, 103117.

Ashraf, U., Salim, M. N., Sher, A., Sabir, S. R., Khan, A., Pan, S., & Tang, X. (2016). Maize growth, yield formation, and water–nitrogen usage in response to varied irrigation and nitrogen supply under semi-arid conditions. Agricultural Water Management, 172, 1–10.

Carsky, R. J., Berner, D. K., Oyewole, B. D., Dashiell, K., & Schulz, S. (2000). Reduction of Striga hermonthica parasitism on maize using integrated soil fertility management. Plant and Soil, 219(1–2), 203–211.

Chimonyo, V. G. P., Snapp, S. S., & Chikowo, R. (2019). Grain legume integration and the productivity of maize-based systems in sub-Saharan Africa: A review. Agronomy for Sustainable Development, 39(3), 1–18.

Duncan, A. J., Thorne, P. J., & Valbuena, D. (2016). Trade-offs and synergies in crop–livestock systems in sub-Saharan Africa: A review. Agricultural Systems, 147, 1–10. https://doi.org/10.1016/j.agee.2016.05.011.

Franke, A. C., van den Brand, G. J., Vanlauwe, B., & Giller, K. E. (2018). Sustainable intensification through rotations with grain legumes in sub-Saharan Africa: A review. Agriculture, Ecosystems & Environment, 261, 172–185. https://doi.org/10.1016/j.agee.2017.09.029

Iqbal, N., Hussain, S., Ahmed, Z., Yang, F., Wang, X., Liu, W., Yong, T., Du, J., Shu, K., & Liu, J. (2019). Comparative analysis of maize–soybean strip intercropping systems: A review. Agricultural Systems, 173, 109–119.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: Their importance, magnitudes, and causes. Annual Review of Environment and Resources, 34, 179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., & Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1(8), 441–446. https://doi.org/10.1038/s41893-018-0114-0

Smale, M., & Jayne, T. S. (2010). Maize in eastern and southern Africa: “Seeds” of success in retrospect (Working Paper No. 97). Michigan State University.

Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., & Kanyama-Phiri, G. Y. (2010). Biodiversity can support a greener revolution in Africa. Proceedings of the National Academy of Sciences, 107(48), 20840–20845. https://doi.org/10.1073/pnas.1007199107

Snapp, S. S., Jayne, T. S., Mhango, W., Benson, T., & Ricker-Gilbert, J. (2014). Maize yield response to nitrogen in Malawi's smallholder production systems.

Steward, P. R., Dougill, A. J., Thierfelder, C., Pittelkow, C. M., Stringer, L. C., Kudzala, M., & Shackelford, G. E. (2018). The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. Agriculture, Ecosystems & Environment, 251, 194-202.

Thierfelder, C., & Wall, P. C. (2010). Rotation in conservation agriculture systems of Zambia: effects on soil quality and water relations. Experimental agriculture, 46(3), 309-325.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A. R., Mupangwa, W., Nyagumbo, I., Kassie, G. T., & Cairns, J. E. (2015). Conservation agriculture in Southern Africa: Advances in knowledge. Renewable Agriculture and Food Systems, 30(4), 328-348.

Vanlauwe, B., Wendt, J., & Giller, K. E. (2014). A fourth principle is required to define conservation agriculture in sub-Saharan Africa: The appropriate use of fertilizer. Field Crops Research, 155, 10–13. https://doi.org/10.1016/j.fcr.2013.10.002

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. SOIL, 1(1), 491–508. https://doi.org/10.5194/soil-1-491-2015

Appendix

Table 1: Seasonal maize grain yields, biomass, mulch cover, and percentage changes between the 2023/24 and 2024/25 seasons.

Treatment	n	2023 Yield (kg ha⁻¹)	2023 Biomass (kg ha⁻¹)	2023 Mulch (%)	2024 Yield (kg ha⁻¹)	2024 Biomass (kg ha⁻¹)	2024 Mulch (%)	Yield Change (%)	Biomass Change (%)
Conventional	43	1,550	2,815	0	1,520	2,980	0	–1.9	+5.9
CA Sole Maize	43	1,750	2,950	35	1,780	3,420	35	+1.7	+15.9
CA Intercrop (Cowpea)	43	3,250	4,250	40	3,267	5,480	45	+0.5	+28.9
CA Intercrop (Lablab)	42	3,150	4,120	28	3,180	5,290	32	+1.0	+28.4
CA Rotation (Cowpea)	43	2,150	3,120	21	2,150	3,850	25	0.0	+23.4
CA Rotation (Lablab)	43	2,050	3,050	18	2,090	3,720	22	+2.0	+21.9

Table 2: Biomass production under different cropping systems

Cropping system / treatment	n	Maize Biomass (kg ha⁻¹, mean ± SD)
Conventional ridge tillage	43	3,420 ± 1,510
CA sole maize	43	3,850 ± 1,420
CA intercrop (maize–cowpea)	43	5,120 ± 2,240
CA intercrop (maize–lablab)	42	5,450 ± 2,510
CA rotation (maize–cowpea)	43	4,210 ± 1,980
CA rotation (maize–lablab)	43	4,180 ± 1,650