



Integrating strip cropping with grass border enhances soil fertility, maize grain, and nutritional yields in Zimbabwean smallholder farming systems

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ABSTRACT

Smallholder maize production in sub-Saharan Africa is constrained by soil fertility decline and erratic rainfall, leading to low dietary diversity. A four-season on-farm study (2018/2019–2021/2022) was conducted with six farmers in Murehwa District, Zimbabwe, to evaluate the effects of maize–legume strip cropping on soil nutrient dynamics, crop yield, and total system nutritional yield. The experiment was a 2×6 factorial arranged in a split-plot randomized complete block design, comparing sole maize with maize strip-cropped with pigeonpea (*Cajanus cajan* (L.) Mills), cowpea (*Vigna unguiculata* L. Walp.), lablab (*Lablab purpureus* (L.) Sweet), velvet bean (*Mucuna pruriens* (L.) DC), and groundnut (*Arachis hypogaea* L.), with and without *Brachiaria* ssp. (cv. Mulato II (CIAT36087) grass border. Rainfall ranged from 495 to 1053 mm, influencing crop and soil responses. Strip cropping affected soil properties between the 2020/21 and 2021/22 seasons, notably pH, exchangeable potassium (K), and soil organic carbon (SOC). Maize + cowpea improved K (+65 %) and pH (+30 %), while maize + groundnut improved SOC (+5 %). Maize grain yield was strongly influenced by season and its interaction with the strip cropping system. Maize + velvet bean yielded 2.4 t ha^{-1} in 2018/19 and 2020/21, although sole maize produced the highest overall yield (3.2 t ha^{-1}). Maize + pigeonpea consistently produced the highest grain yield among legumes ($\approx 1.0 \text{ t ha}^{-1}$) and total system protein yield ($> 0.3 \text{ t ha}^{-1}$), while starch yield was highest under sole maize in 2020/21. Overall, maize–legume strip cropping, particularly pigeonpea, cowpea, and groundnut, improved system-level nutrient yield and selected soil properties, demonstrating its potential for climate-resilient smallholder farming.

1. Introduction

Food and nutrition insecurity remains a critical challenge in southern Africa, affecting the physical, social, intellectual, and economic capacities of its population (Siddiqui et al., 2020), and contributing to low agricultural productivity and entrenching poverty among smallholder communities (Nhemachena et al., 2020; Nyoni et al., 2022). Since the 1990s, the nutritional status of smallholder farmers in the region has eroded, mainly due to reliance on maize-based diets supplemented with only small amounts of animal protein or legumes (Nyakurwa et al., 2017). Protein malnutrition currently affects 47–54 % of the African

population, posing a significant public health concern, contributing to high rates of severe malnutrition and mortality (Adeyeye et al., 2017; Lonnie et al., 2018). Alarming, the prevalence of malnutrition is projected to double by 2050 (Nakashima et al., 2022).

Climate change further exacerbates food insecurity in semi-arid regions through recurrent droughts, heat stress, and rainfall variability (Nhemachena et al., 2020). Traditionally, farmers in these regions grew nutrient-dense small grains (Musidzaramba et al., 2025) such as pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet (*Eleusine coracana* (L.) and sorghum (*Sorghum bicolor* (L.). However, over the past 150 years, a strong dietary and production shift toward maize (*Zea mays* L.)

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has occurred (Ncizah et al., 2021). Maize is now the dominant staple crop and primary source of dietary carbohydrates in the region, produced by both commercial and smallholder farmers (Liu et al., 2020; Ndhlela et al., 2014). Maize production in Zimbabwe is increasingly constrained by declining soil fertility, erratic rainfall, invasive pests such as fall armyworm (*Spodoptera frugiperda* J.E. Smith), diseases, weeds, unsustainable agronomic practices, and limited access to inputs and markets (Baudron et al., 2019; Madembo et al., 2020). External shocks such as the Ukraine-Russia war and the COVID-19 pandemic further intensified these challenges by hiking fuel, input, and food prices, disrupting labour supplies, and reducing household purchasing power (Jagtap et al., 2022; Nchanji and Lutomia, 2021). Meanwhile, rapid population growth has accelerated land fragmentation, leaving most farmers with fields of less than 3 ha for household production (Makate et al., 2016).

As a result, smallholder maize yields in Zimbabwe often remain below $1 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Nyagumbo et al., 2020), which is not enough to support a rapidly growing population (Fisher et al., 2015). This production gap threatens progress toward the United Nations' Sustainable Development Goal 2 (Zero Hunger). The dominance of conventional tillage (CT) and monocropping, based on soil inversion using mould-board ploughs and similar implements, further undermines system resilience (Nyakudya and Stroosnijder, 2015). Such practices accelerate soil erosion, nutrient losses, greenhouse gas emissions, and biodiversity loss (Haarhoff et al., 2020; Kihara et al., 2020).

In response, legume-based intercropping has been promoted as a climate-smart strategy to address soil fertility decline, dietary diversity, and system-level productivity. Legumes enrich soil through biological nitrogen fixation, improve soil structure, supply dietary protein, and partially reduce dependence on synthetic fertilizers (Nyamayevu et al., 2024; Thierfelder et al., 2024). Their inclusion can also raise protein, starch, and oil yields, which are metrics increasingly emphasized in assessing food system resilience and human nutrition (Nyamayevu et al., 2024; Thierfelder et al., 2024).

Among different intercropping methods, strip cropping is gaining increasing attention for its agronomic and ecological benefits (Thierfelder et al., 2024; Toker et al., 2024). This spatial arrangement of alternating strips of cereals and legumes mainly reduces competition for light between the two species (Toker et al., 2024) and improves productivity (Thierfelder et al., 2024; Veres et al., 2020). Strip cropping can also limit soil erosion and is compatible with mechanization options suited to smallholder contexts (Juventia et al., 2025; Rehman et al., 2025). Current efforts in Zimbabwe and Zambia are testing scale-appropriate mechanization to make strip cropping feasible for resource-constrained farmers (Baudron et al., 2015; Shonhe, 2022). The performance of strip cropping, however, depends strongly on climatic conditions, species traits, and strip configurations (Iqbal et al., 2019; Juventia et al., 2022).

Additional benefits may be achieved by integrating strip cropping with trap crops such as *Brachiaria* spp. grasses in border rows. Included in climate-smart push–pull systems in East Africa, *Brachiaria* spp. planted as a border crop may attract stemborers and fall armyworm, whilst intercropped legumes between maize rows may repel them, effectively reducing crop damage by these insect pests (Kebede et al., 2018; Midega et al., 2018). Beyond pest control, *Brachiaria* borders enhance moisture retention and provide high-quality fodder (Murage et al., 2015). Combined with legume strip cropping, *Brachiaria* borders may generate synergistic benefits for maize yield, soil health, and protein-rich food production.

However, despite promising evidence from East and Southern Africa, adoption and testing of maize-legume strip cropping with *Brachiaria* borders remain limited in Zimbabwe's rainfed smallholder systems. Knowledge gaps persist regarding the combined effects of these factors on crop yield, soil properties, and system-level nutritional outputs across various agroecological conditions in Zimbabwe.

The objective of this study was therefore to evaluate the effects of

maize-legume strip cropping options, with and without *Brachiaria* grass borders, on maize productivity, soil quality indicators, and system-level nutritional yield under rainfed smallholder farming systems. We hypothesized that i) combining *Brachiaria* borders with maize-legume strip cropping enhances maize productivity and soil quality under rainfed smallholder farming systems, and ii) maize-legume strip cropping improves overall system-level protein, starch, and oil yields compared with sole maize in rainfed smallholder farming systems.

2. Materials and methods

2.1. Study area

The experiment was established in Ward 4 of the Murehwa district, Zimbabwe, over four consecutive cropping seasons (2018/2019, 2019/2020, 2020/2021, and 2021/2022). The experimental site was located in Mashonaland East Province (geographical coordinates: -17.477° S , 31.729° E , with an elevation of 1119 m above sea level). Murehwa district lies in agroecological region IIb of the Zimbabwean agroecological zones, with an annual rainfall of 800 to 1000 mm (Madembo et al., 2020). It is prone to frequent and severe dry spells during the rainy seasons. The rainy season typically begins in October or November and lasts until April/May, with the peak rainfall period occurring from December to February. Maximum daily temperatures sometimes exceed 32° C and are experienced from September to December. The lowest temperatures, of 14° C , were recorded during the May–July period. The district is dominated by sandy soils (*Haplic Lixisols* and *Arenosols*) derived from granitic bedrocks (Soropa et al., 2019).

Murehwa district represents a typical smallholder farming system in the semi-arid regions of southern Africa, where maize is the dominant staple crop grown under challenging environmental conditions, including erratic rainfall, poor soil fertility, and frequent droughts. These characteristics make it a relevant and representative site for evaluating the impact of strip cropping and legume integration on soil health, maize grain, and nutritional yield. Major crops grown in the districts, apart from maize, include sweet potatoes (*Ipomoea batatas* (L.) Lam.), groundnut, cowpea, bambara nuts (*Vigna subterranea* (L.) Verdc), soybean (*Glycine max* L.), and common bean (*Phaseolus vulgaris* L.). Large and small livestock rearing is also common in the area, featuring a diverse range of animals, including cattle, goats, sheep, rabbits, and chickens.

2.2. Farmer selection criteria and experimental design

The farmers used in this study were selected based on:

- the farmers' willingness to collaborate and adhere to standardized management practices during the study period,
- availability of sufficient land area to accommodate all experimental treatments, and
- farms to be representative of the variability, mainly in soil types, management practices, and environmental conditions, expected to be found in the study area.

The experiment was set up as a 2×6 factorial arranged in a split-plot design within a randomized complete block design (RCBD). The main plot treatments consisted of two grass border levels, with and without a *Brachiaria* grass border, while the subplot treatments comprised six strip cropping systems, namely:

- Sole maize (Mz) – control
- Maize + pigeonpea (Mz + pp) strip cropping
- Maize + cowpea (Mz + cp) strip cropping
- Maize + lablab (Mz + ll) strip cropping
- Maize + velvet bean (Mz + vb) strip cropping
- Maize + groundnut (Mz + gn) strip cropping

The experiment was conducted on six farmers' fields, serving as replications. The experiment was repeated in the 2018/2019, 2019/2020, 2020/2021, and 2021/2022 cropping seasons. Each subplot measured 10 m × 10 m (100 m²) (see [Scheme 2](#)).

2.3. Plot management practices

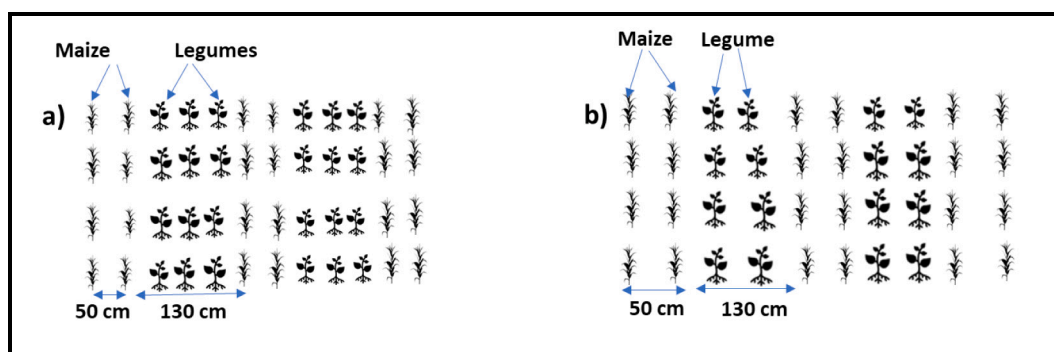
Crop residues were predominantly removed from the fields by farmers for alternative household uses such as livestock feed or fuel material. However, a small proportion (about 5–10 %) of the residues remained in situ. These residual materials gradually decomposed or were grazed by free-ranging animals over time.

Land preparation with a mouldboard plough commenced between October and November of each cropping season using animal traction. During seeding time, planting basins (0.15 m length × 0.15 m width × 0.15 m depth) were established using a hand hoe to ensure precise seed placement. The two blocks (grass and no grass) were separated by a 30 m × 30 m (900 m²) area where sole maize was planted in rip lines under no-tillage. This spatial division aimed to prevent interference between the main treatments and to reduce external influences, thereby enhancing the accuracy and validity of data collected from the grass border and strip cropping systems. This was particularly important as the trial was also used to assess pest control (data not presented here).

The strip cropping width was 1.80 m, with two maize rows occupying 0.50 m and the legumes occupying 1.30 m within the designated sub-treatments ([Schemes 1 and 2](#)). Two rows of *Brachiaria* ssp. forage grass, spaced 50 cm apart, was established during the 2018/19 cropping season to surround the maize strip cropping plots at all six farmer fields. The commercial maize variety PAN 53 (medium maturing hybrid) was sown simultaneously with all the legumes except the velvet bean, which was planted three weeks after maize planting to avoid excessive crop competition. The in-row spacing for maize was 0.50 m, with two plants per station, resulting in a plant population of approximately 44,000 plants ha⁻¹. Velvet bean, pigeonpea, and lablab were sown in two rows each, and in each strip, they were spaced at 0.5 m × 0.5 m. Groundnut and cowpea, on the other hand, were sown in three rows at 0.3 m × 0.3 m spacing ([Scheme 1](#)). The maize and legume strips were alternated in each cropping season.

After planting, a pre-plant non-selective foliar herbicide (glyphosate [N-(phosphonomethyl) glycine]) was applied (480 g L⁻¹ active ingredient) at a rate of 2.5 L ha⁻¹ using a knapsack sprayer to control weeds. Manual weeding using hand hoes was performed whenever weeds reached 10 cm in height or circumference, particularly for those with a stoloniferous growth habit.

A basal fertilizer (7N:14P₂O₅:7K₂O) was applied to maize at planting at 150 kg ha⁻¹, and top dressing with ammonium nitrate (34.5 % N) was equally split applied (at four and seven weeks after planting) at 150 kg ha⁻¹ (51.3 kg N ha⁻¹) total application rate. Legumes did not receive any soil fertility amendments throughout the study period.



Scheme 1. Maize and legume rows in a strip cropping design: a) showing arrangement of groundnut and cowpea, and b) showing lablab, velvet bean, and pigeonpea planted in strip cropping with maize.

2.4. Data collection

2.4.1. Daily rainfall and temperature

A standard rain gauge (conical shape) was installed at each farmer's field and used to measure daily rainfall throughout the study period. The rainfall was recorded daily before 09:00 a.m. Temperature data were obtained from NASA Power ([NASA POWER | Data Access Viewer \(DAV\)](#), 2023).

2.4.2. Soil samples

Soil samples were collected from each farmer's field for field characterization using a soil auger. Soil samples were collected directly from the treatment plots at a depth of 0–20 cm, both before the 2021 planting and at the end of the 2022 cropping season, to indicate soil conditions across participating farms. However, due to limited funding at the onset of the study and the high costs associated with comprehensive soil analyses, baseline soil samples were not collected before trial establishment. Soils were sampled at six random positions in each treatment of the farmer's field and were thoroughly mixed to create a composite sample that was later sieved through a 2 mm mesh. The samples were analyzed at the Chemistry and Soils Research Institute (CSRI) Laboratory under the Department of Research and Specialist Services (DR&SS) in Zimbabwe. Parameters of interest were soil pH, available nitrogen, phosphorus, and exchangeable potassium, magnesium, calcium, and sodium, and soil organic carbon, which are key soil parameters that influence plant nutrient availability. The different soil analysis methods used are listed in [Table 1](#) and are standard laboratory procedures for soil analysis.

2.4.3. Maize and legume grain yields determination

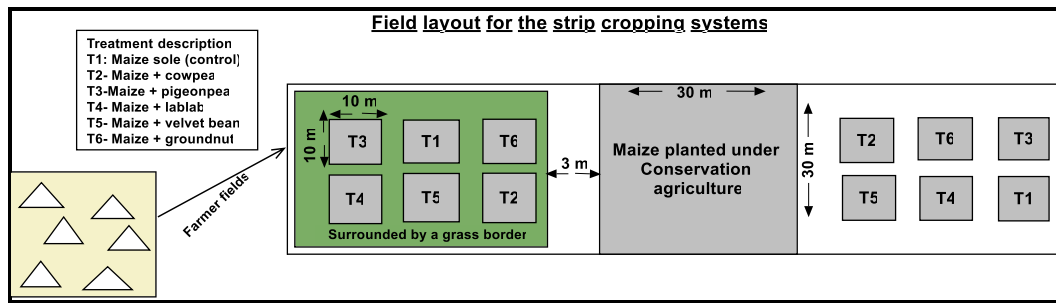
All crops were harvested each season after reaching their physiological maturity (April–June) from 10 m × 10 m plots (net plot of 3 paired strips of 2 rows by 5 m for maize, pigeonpea, velvet bean, and lablab, and 3 triplet strips of 3 rows by 5 m for cowpea and groundnut). Ears/pods were manually separated from the stalks, and total field fresh weights were recorded. Grain subsamples (randomly selected 10 cobs for maize and 500 g for legumes) from each treatment were air-dried (at least 7 days) for dry matter determination. Maize and legume grain yields were then determined at 12.5 % and 9 % moisture basis, respectively, from the net plot sub-sample of each plot using Eq. (1). The grain yield was then calculated on a hectare basis.

$$\text{Adjusted grain yield} = \text{Actual grain yield} \times \frac{(100 - A)}{(100 - U)} \quad (1)$$

where A = measured grain moisture of maize or legumes, and U = the desired moisture storage content (maize 12.5% and legumes 9%).

2.4.4. Maize grain nutrient yield determination

Maize grain samples (approximately 300 g per treatment) from the



Scheme 2. Field plan for each farmer replicate. Treatments were randomized at each farmer's field.

Table 1
Determination of soil parameters and their methods.

Parameter	Method	Reference
Colour	Munsell Colour Chart	
Texture	Hand texturing	(Thien (1979))
Nitrogen (N)	KCl extraction method + colorimetric using UV-VIS spectrometer	Mulvaney (1996)
Available phosphorus (P)	Resin method + UV-VIS spectrometer	Barberis et al. (1995)
Potassium (K), magnesium (Mg), and sodium (Na)	Ammonium acetate extraction + Atomic Absorption Spectrometry	Sumner and Miller (1996)
Soil organic carbon (SOC)	Wet oxidation + Titration	Nelson and Sommers (1996)
pH	CaCl ₂ method in 1:5 soil:solution	Eckert and Sims (1995)

2020–2021 and 2021–2022 cropping seasons were analyzed for protein, starch, and oil content using a Foss Infratec™ 1241 grain analyzer (Foss Allé, Hillerød, Denmark) at the International Maize and Wheat Improvement Centre (CIMMYT), Harare, Zimbabwe. Before analysis, each grain sample was ground and thoroughly homogenized to ensure uniformity. The nutrient concentrations obtained from the analyzer were initially expressed on an “as-is” basis, reflecting the moisture content of each sample at the time of scanning. To ensure consistency and comparability with legume nutrient data sourced from Feedipedia (which are reported on a dry matter basis), all maize nutrient values were converted to a dry matter basis using the actual measured moisture content of each sample (Eq. 2).

$$\text{Nutrient}_{\text{dry matter}} = \frac{\text{Nutrient}_{\text{as-is}}}{1 - \text{moisture fraction}} \quad (2)$$

For total system nutritional yield, values for the sole maize system were derived exclusively from maize grain. While for the strip cropping systems, which involved both maize and legume crops (cowpea, groundnut, pigeonpea, lablab, and velvet bean), we included the grain yield of both crops in the total nutritional output calculations. This approach reflects the integrated nutritional contribution of the full cropping system. The nutritional contents/ ratios used for legumes are presented in Table S1, and the procedure for calculating the total system's nutritional yield is therefore outlined in Table S2.

2.5. Data analysis

Statistical analyses were performed in R Version 4.4.2 (R Core Team, 2024), separately for maize grain yield, legume grain yield, and total system nutrient yield. To assess treatment effects on maize grain yield, total system grain nutrient yield, soil pH, and soil chemical nutrients, a linear mixed-effects model (LMER) was fitted using the lmer() function in the lme4 package in R (Bates et al., 2015).

2.5.1. Model 1: maize yield and total system grain nutrient yield

The model used to analyze maize grain yield and total system

nutrient yield was specified as: Response $\sim$ Border $\times$ Strip cropping system $\times$ Season + (1 | Farmer) + (1 | Farmer:Border) + (1 | Farmer:Border:Strip cropping system), data = data.

Here, *Farmer* $\times$ *Border* accounts for potential differences in field management or micro-environmental conditions among farmers. At the same time, the *Border* $\times$ *Strip cropping system* captures treatment responses that may vary depending on whether plots were located at the border or interior positions. The *Season* $\times$ *Strip cropping system* interaction assesses the stability of treatment responses under varying climatic conditions. Random effects were specified to account for variability among farmers and nested experimental units, with random intercepts for farmer, farmer-by-border, and farmer-by-border-by-strip cropping system combinations.

Random effects were specified for (1 | *Farmer*) and (1 | *Farmer:Border*) to account for repeated measures within each farmer-border combination, and (1 | *Farmer:Border:Strip cropping system*) to model the random variation among treatment applications nested within each farmer-border unit. These random structures appropriately reflect the hierarchical and split-plot nature of the experimental design, addressing non-independence of observations within farmers and across treatments.

2.5.2. Model 2: soil pH and soil chemical properties

The model for soil pH and soil nutrient concentrations was specified as: Response $\sim$ Border $\times$ Strip cropping system + (1 | Farmer) + (1 | Farmer:Border), data = data.

In this model, *Farmer*, *Border*, and *Strip cropping systems* were considered as fixed effects, while (1 | *Farmer*) and (1 | *Farmer:Border*) were included as random effects to account for inter-farmer variability and subplot nesting within farmers.

2.5.3. Model evaluation and inference

Model assumptions were verified by examining residual plots for normality and homoscedasticity. The significance of fixed effects was evaluated using Type III ANOVA with the Kenward-Roger approximation for degrees of freedom, implemented via the lmerTest package (Kuznetsova et al., 2017). When significant main or interaction effects were detected, post-hoc pairwise comparisons were adjusted using Tukey's HSD through the emmeans package (Hou et al., 2021), complemented by agricolae and multcompView for compact letter display. Variance components were extracted to quantify the contribution of each random term.

This analytical framework ensured proper handling of hierarchical error structures and provided robust inference for treatment effects on yield and soil responses.

3. Results

3.1. Rainfall distribution

Rainfall amounts and distribution varied across seasons during the study period. The district received a total annual rainfall of 825 mm,

495 mm, 1053 mm, and 654 mm in the 2018/2019, 2019/2020, 2020/2021, and 2021/2022 cropping seasons, respectively, from the onset of the rainy season. Throughout the study period, the district encountered dry spells during cropping seasons (Fig. S1). Cropping seasons 2018/2019 and 2020/2021 recorded a temperature range of 16–23 °C, 2019/2020 had 17–23 °C, and 2021/2022 recorded 15–23 °C, respectively.

3.2. Effects of cropping systems on soil nutrient dynamics

Fig. 1 illustrates the association between soil pH levels measured during the 2020/2021 and 2021/2022 cropping seasons under various strip cropping systems in Ward 4 of Murehwa district. Across all systems, regression slopes were positive and significant, indicating that soil pH values in the second season were strongly associated with those recorded in the first season. The strength of association varied by strip cropping system, with the highest correlation observed in maize + cowpea ($R = 0.84$, $P < 0.001$), and a significant association was also observed under maize + lablab ($R = 0.67$, $P < 0.05$).

Strip cropping system significantly ($P < 0.05$) affected the change in soil pH between the cropping seasons 2020/21 and 2021/22 (Table S3). The soil pH results revealed contrasting effects of the different strip cropping systems between 2020/21 and 2021/22 (Fig. 2). Soil pH increased slightly under Mz + cp (30 %) but declined under all other strip cropping systems, with the steepest decline observed in Mz + vb (–122 %).

The strip cropping system had a significant effect on soil available K and SOC ($P < 0.001$ and $P < 0.05$, respectively), between seasons 2020/21 and 2021/22 (Table S3). However, no significant effects were observed on other soil chemical nutrients, including N, P, Mg, Na, and

Ca. The change in soil K in 2021/22 relative to 2020/21 differed among the strip cropping systems (Fig. 3A). The Mz + cp strip cropping system improved soil K by 65 %. In contrast, all other systems showed declines in K. Mz + gn was the only system associated with a positive change in SOC (+5 %); all other systems showed negative mean changes (Fig. 3B). On the other hand, with and without *Brachiaria* border treatment increased the soil available Ca by 12 % and 56 %, respectively (Fig. S2).

3.3. Maize and legume crop performance across seasons

Results indicate that cropping season and the interaction between season and strip cropping system had a significant effect on maize grain yields (Table S4). Higher maize grain yields were observed in the 2020/2021 cropping season, with an average yield of 2.4 t ha⁻¹ compared to other cropping seasons, while the lowest yields were recorded in the 2019/2020 season, with an average of 1.4 t ha⁻¹ (Fig. 4A). There was also a significant interaction between cropping season and strip cropping system for maize grain yield ($P < 0.01$), indicating that treatment effects were not consistent across years (Table S4, Fig. 4B). Mz sole produced the highest average yield in the 2018/2019 and 2020/2021 seasons (2.9 t ha⁻¹ and 3.2 t ha⁻¹, respectively), significantly outperforming strip crops (Fig. 4). In contrast, the 2019/2020 and 2019/2020 seasons showed no significant differences among treatments.

Season, strip cropping system, and their interaction had a significant effect ($P < 0.05$) on legume grain yields (Table S4). All cropping seasons had legume grain yields that were lower than 1 t ha⁻¹ (Fig. 5A). The highest grain yields (0.5 t ha⁻¹) were observed during the 2018/2019 cropping season, and the lowest yield of 0.2 t ha⁻¹ was observed during the 2020/2021 cropping season. Higher mean legume grain yields were

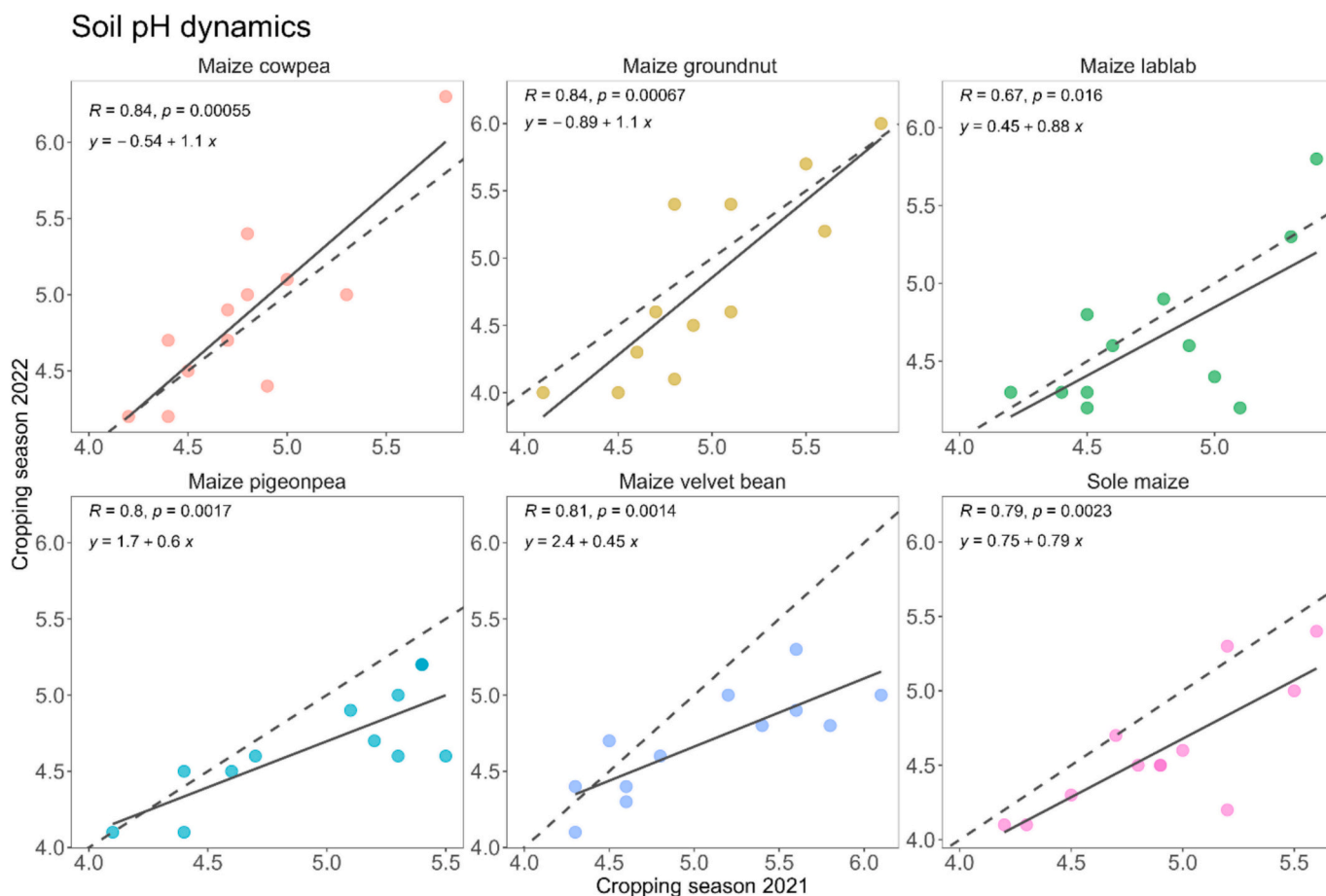


Fig. 1. Relationship between soil pH measured in the 2020/21 and 2021/22 cropping seasons under different strip cropping systems in Ward 4, Murehwa district. Solid lines represent fitted regressions; dashed lines denote the 1:1 line.

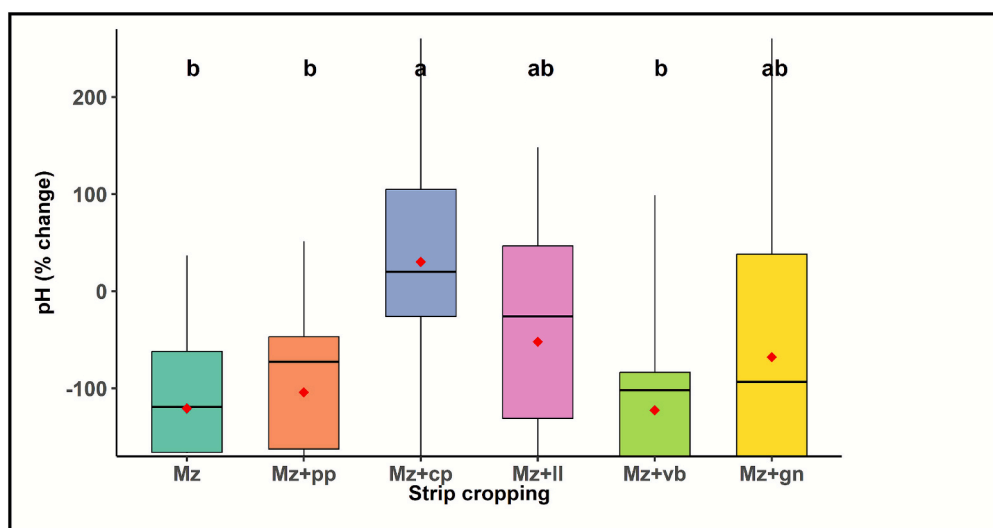


Fig. 2. Influence of strip cropping system on soil pH. Abbreviation: Mz = sole maize, Mz-pp = Maize-pigeonpea, Mz-cp = Maize-cowpea, Mz-ll = Maize-lablab, Mz-vb = Maize-velvet bean, and Mz-gn = Maize-groundnut. The black diamond-shaped symbols indicate the mean nutrient of each factor. Treatments with different superscripted letters are significantly different at a 95 % confidence level.

observed from Mz + pp strip cropping (1 t ha^{-1}), and the lowest mean legume grain yield was observed on Mz + gn strip cropping with 0.2 t ha^{-1} (Fig. 5B). Across all seasons, Mz + pp strip cropping consistently produced the highest average legume grain yield, significantly exceeding that of other strip crops (Fig. 5C). However, the relative performance of other legume strip crops varied by season. In 2018/19, Mz + ll showed intermediate yield levels, while Mz + cp, Mz + vb, and Mz + gn recorded the lowest yields. In 2019/20 to 2021/22, the yield advantage of Mz + pp was more pronounced, with no significant differences among other strip crops (Fig. 5C).

Additionally, the significant interaction between border and season was observed for legume grain yield, primarily due to the effect of growing seasons (Table S4). Overall, yields were highest in 2018/19 and 2021/22 and lowest in the 2020/21 season (Fig. 6A). Within seasons, with and without *Brachiaria* border plots did not differ significantly. A significant interaction was also observed between season, border, and strip cropping for legume grain yield, indicating that the effect of strip cropping varied across borders and growing seasons (Table S4). Across all seasons, pigeonpea consistently outperformed other legume species, producing the highest grain yields under both border treatments. In the 2018/19 and 2019/20 seasons, characterized by above-average rainfall, pigeonpea yields exceeded 0.9 t ha^{-1} without *Brachiaria* and reached $1.0\text{--}1.4 \text{ t ha}^{-1}$ with *Brachiaria* borders (Fig. 6B). In contrast, short-duration legumes such as cowpea, lablab, velvet bean, and groundnut recorded significantly lower yields ($\leq 0.5 \text{ t ha}^{-1}$) during the same period. During the 2020/21 season, yields declined markedly across all systems, averaging below 0.8 t ha^{-1} , with pigeonpea remaining relatively stable compared to other legumes. By the 2021/22 season, legume yields rebounded, particularly for pigeonpea (1.5 t ha^{-1} without *Brachiaria* and 0.8 t ha^{-1} with *Brachiaria*), reflecting improved rainfall distribution and favourable soil moisture conditions.

3.4. Effects of season and strip cropping system on total system protein, starch, and oil yield

Strip cropping system and its interaction with season significantly influenced total system protein yield ($P < 0.001$, Table S5). Among strip cropping systems, Mz + pp consistently resulted in a significantly higher total system protein yield (0.34 t ha^{-1}), while Mz sole produced the lowest (0.15 t ha^{-1}) (Fig. 7A). Seasonal variation further affected treatment performance. In 2020/21, M + pp strip crop achieved the highest total system protein yield (0.3 t ha^{-1}), significantly exceeding

other strip crops and Mz sole (Fig. 7B). In 2021/22, the treatment rankings shifted, with M + pp again remaining superior (0.38 t ha^{-1}), followed by M + ll (0.25 t ha^{-1}), while Mz sole declined markedly to 0.09 t ha^{-1} .

The season and the interaction between season and strip cropping system significantly influenced the total system starch yield ($P < 0.01$ and $P < 0.05$, respectively; Table S5). In 2020/21, the average total system starch yield was highest at 1.9 t ha^{-1} , while in 2021/22 it declined significantly to 1.5 t ha^{-1} (Fig. 8A). Furthermore, in the 2020/21 season, Mz sole produced the highest starch yield (2.5 t ha^{-1}), significantly outperforming strip crops (Fig. 8B). In contrast, during the 2021/22 season, no significant differences were observed among treatments, indicating a narrowing of treatment effects under the conditions of the season.

4. Discussion

4.1. Seasonal effects on crop performance

Our findings revealed non-uniform rainfall patterns and distribution, as well as prolonged mid-season dry spells (up to 13 days), particularly during the cropping seasons 2018/19 and 2019/20. This may have disrupted the uptake and utilization of mineral nutrients from the soil due to the gradual depletion of soil moisture. Reduced soil moisture limits the dissolution and mobility of nutrients, thereby impairing their availability for plant uptake. As a result, intra-plant competition for limited resources may have intensified, ultimately lowering overall grain yield, especially during critical growth stages (Bouhenache et al., 2025). Bouhenache et al. (2025) and García-Lara and Serna-Saldivar (2019) demonstrated that poor rainfall distribution reduced nutrient use efficiency, particularly nitrogen and maize productivity in the SSA region, including Zimbabwe, even when total seasonal rainfall was adequate. Additionally, the onset of the cropping season was delayed, while the end of the cropping season was earlier, thereby shortening the overall cropping season. This may have adversely impacted critical crop growth stages, including flowering and grain filling, resulting in poor crop development and ultimately crop yields. These threats were previously analyzed in studies for Zimbabwe (Mhlanga et al., 2015) and represent significant risks in smallholder farming systems in southern Africa, which are highly dependent on rainfed agriculture. Future projections suggest that maize-based cropping systems in Zimbabwe will increasingly be affected by climate disruption, requiring adaptation to a

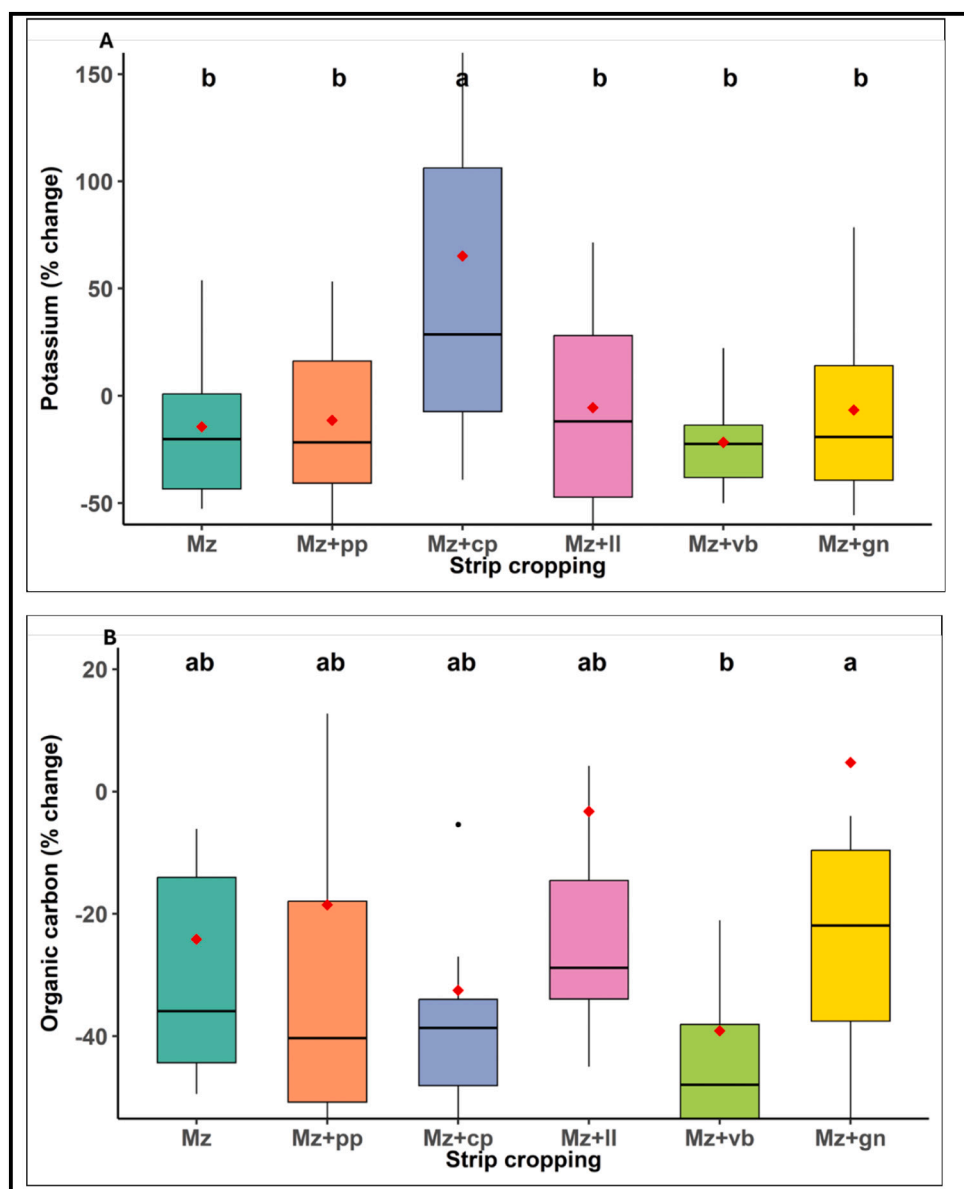


Fig. 3. Effects of strip cropping system on soil available potassium and organic carbon. Abbreviation: S-mz = sole maize, M + pp = Maize-pigeonpea, M + cp = Maize + cowpea, M + ll = Maize + lablab, M + vb = Maize + velvet bean, and M + gn = Maize + groundnut. The black diamond-shaped symbols indicate the mean nutrient content. Treatments with different superscripted letters are significantly different at a 95 % confidence level.

changing climate.

4.2. Strip cropping systems and soil quality dynamics

Strip cropping systems significantly influenced key soil chemical parameters, with outcomes influenced by crop combinations between the 2020/21 and 2021/22 seasons. The Mz + cp system uniquely increased soil pH and extractable K, while most other maize-legume strips and Mz sole showed declines in pH, K, and SOC. Similar findings were reported by [Netthisinghe et al. \(2023\)](#), who observed that legume-based systems can enhance soil pH through biological nitrogen cycling and organic matter contributions. Short-duration legumes such as cowpea appear particularly effective in buffering acidification and enhancing nutrient cycling, though species differ in their impacts on soil chemistry ([Akchaya et al., 2025](#); [Teng et al., 2024](#)).

Root exudates from maize and legumes release organic acids that dissociate and liberate protons (H^+) ([Ma et al., 2022](#); [Zhang et al., 2024a](#)). During N fixation, proton release can temporarily acidify the

rhizosphere, while nutrient leaching and the differential uptake of cations such as Ca^{2+} , Mg^{2+} , and P alter soil pH depending on texture and nutrient balance ([Sirisuntornlak et al., 2021](#)). The contrasting pH responses observed among systems likely reflect differences in root exudate composition, residue quality, decomposition rates, microbial activity, and nutrient uptake patterns ([Markos and Yoseph, 2024](#); [Zhang et al., 2024b](#)). Velvet bean, for instance, produces abundant, rapidly decomposing biomass that can accelerate organic acid release and lower soil pH ([Sujatha et al., 2024](#)). The studied soils, being moderately acidic, are prone to P fixation and aluminum toxicity, which can reduce maize yields, emphasizing the need for crop combinations that maintain favourable soil pH for nutrient availability and productivity.

The strong positive response of extractable K under Mz-cp was likely driven by (i) increased recycling of K through cowpea biomass and roots, which return nutrients to the topsoil during residue decomposition, and (ii) improved nutrient retention under residue retention and minimum soil disturbance ([Abdoul-Karim et al., 2025](#)). Similar effects have been documented in smallholder systems, where residue retention and crop

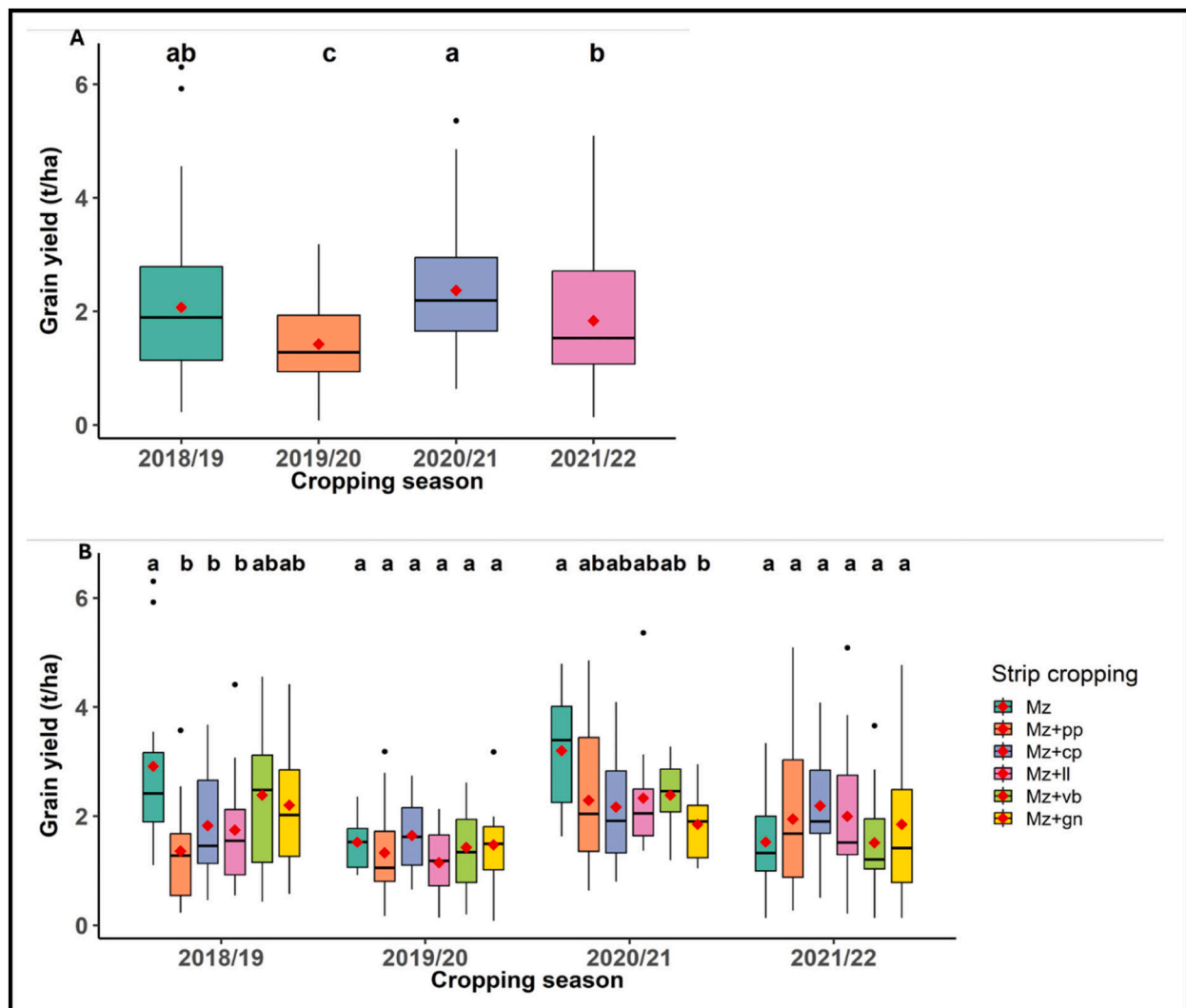


Fig. 4. Boxplots showing the effects of season and the interaction between season and strip cropping system on maize grain yield. Codes: Mz = sole maize, Mz + pp = Maize + pigeonpea, Mz + cp = Maize + cowpea, Mz + ll = Maize + lablab, Mz + vb = Maize + velvet bean, and Mz + gn = Maize + groundnut. The red diamond-shaped symbols indicate the mean grain yield of each factor (A–B). Treatments with different superscripted letters are significantly different at a 95 % confidence level.

diversification reduce subsoil K mobilization (Andrews et al., 2021; Rusinamhodzi et al., 2016). Conversely, systems with rapid SOC loss or residue removal tend to deplete K stocks (Islam et al., 2023). Root exudates from maize and legumes may further facilitate K^+ solubilization. However, other legumes in this study generally exhibited declines in extractable K after one season. This may be attributed to their deeper root systems and higher K demand, which can lead to greater K uptake and depletion from subsoil layers. This aligns with findings that species-specific rooting depth and nutrient demand influence K dynamics (Phiri and Njira, 2023). In Mz + vb systems, K depletion often results from higher uptake associated with vigorous biomass production (Yang et al., 2024). Furthermore, pigeonpea and groundnut tend to access and extract K from deeper soil horizons, where replenishment is slower, especially under low-input conditions (Balpande et al., 2016). Additionally, these legumes often accumulate more biomass, which increases total nutrient uptake, including K, and may result in reduced residual K levels in the soil (Balpande et al., 2016).

The Mz + gn strip cropping system uniquely increased SOC over the two cropping seasons, contrasting with SOC declines observed in other treatments, such as Mz + vb. Groundnut residues, with their balanced carbon: nitrogen ratio and moderate lignin content, promote microbial activity while supporting carbon stabilization (Witcombe and Tiemann,

2022; Yila et al., 2023). Groundnut's fibrous root system and canopy cover further enhance belowground carbon inputs and reduce erosion losses. Meta-analyses confirm that residue retention and cover cropping can increase SOC by 9–10 %, while manure inputs can raise it by up to 30 %, depending on biomass quality, soil type, and climate (Bolinder et al., 2020).

In contrast, legumes like velvet bean, despite producing high biomass, decompose rapidly due to their low lignin and high N content, leading to short-term carbon losses through accelerated mineralization and oxidation (Arunrat et al., 2020). These losses are further amplified in sandy soils with limited physical protection of organic matter, hence slow SOC build-up (Mbanjwa et al., 2023). The short study duration likely limited the detection of SOC change, as organic matter turnover occurs slowly (Yu et al., 2021). Nonetheless, SOC losses could potentially be mitigated through residue retention, reduced tillage, and the use of organic amendments, such as farmyard manure (Franzluebbers et al., 2020). Ultimately, the capacity of legumes to maintain or enhance SOC under strip cropping remains context-dependent, shaped by soil type, climate, and biomass production levels (Wang et al., 2025b).

Furthermore, without *Brachiaria* border treatment, exhibited larger gains in available Ca relative to *Brachiaria* border treatment. This indicates that crop roots likely accessed more Ca in the soil profile,

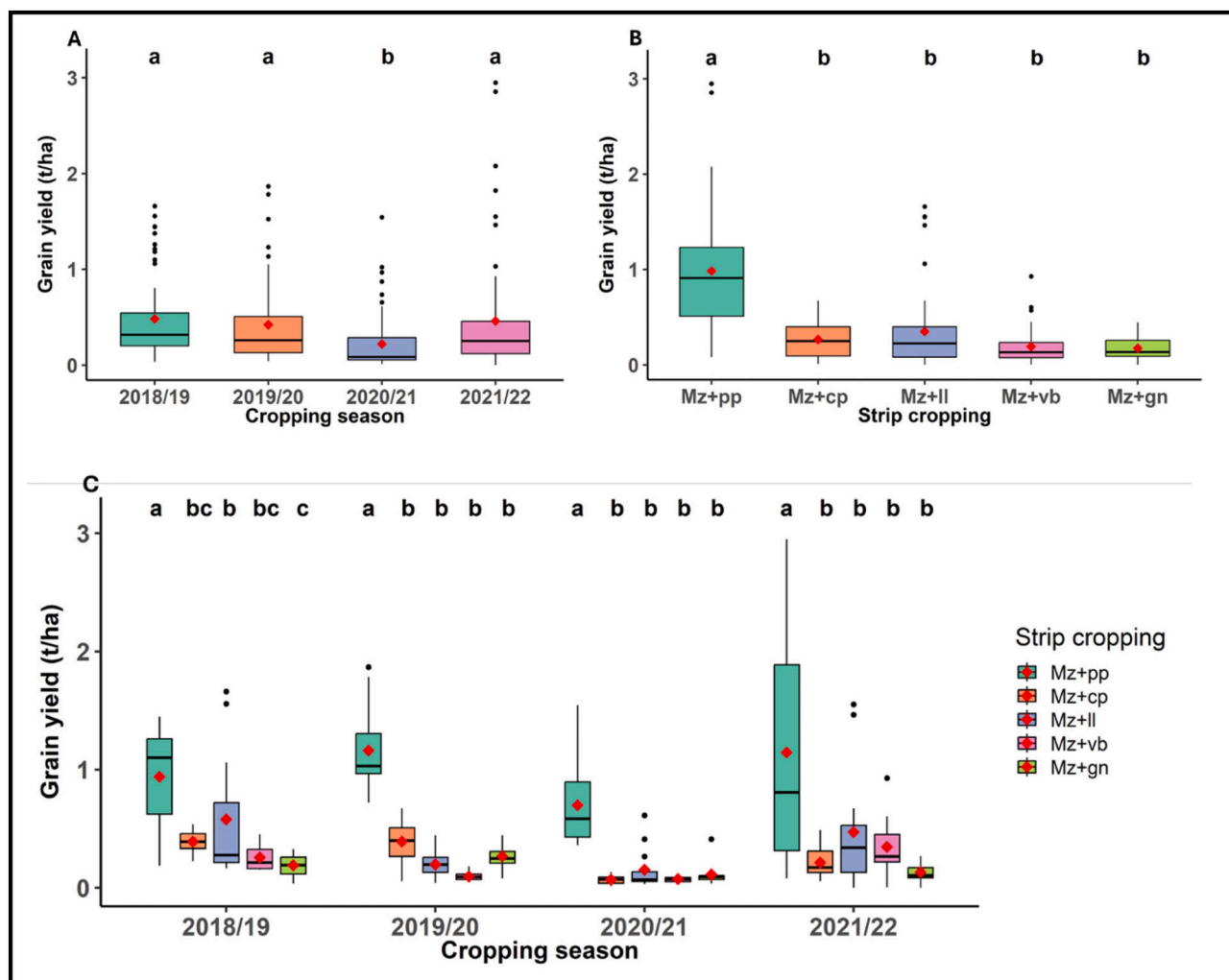


Fig. 5. Boxplots showing the influence of season, strip cropping, and the interaction between season and strip cropping system on legume grain yields. Codes: Mz + pp = Maize + pigeonpea, Mz + cp = Maize + cowpea, Mz + ll = Maize + lablab, Mz + vb = Maize + velvet bean, and Mz + gn = Maize + groundnut. The red diamond-shaped symbols indicate the mean legume grain yield of each factor (AC). Treatments with different superscripted letters are significantly different at a 95 % confidence level.

benefiting from less competition (Yang et al., 2024). Furthermore, literature showed that when rainfall is modest, the absence of vegetative barriers allows more concentrated nutrient cycling, supporting higher extractable Ca (Dimande et al., 2024). However, vegetative borders (*Brachiaria*) can alter edge nutrient dynamics through competition for water and mobile nutrients or by altering lateral nutrient flows (Fu et al., 2023) supported the findings. While vegetative barriers are widely reported to reduce erosion and improve aggregate stability, they can also sequester nutrients at the margin, reducing their immediate availability within the cropped strip if competition for shallow soil resources is strong (da Silva et al., 2021; Nacinovic et al., 2024).

4.3. Impact of strip cropping systems on maize and legume grain yields

Maize grain yields varied significantly across seasons and among strip cropping systems, largely reflecting the influence of seasonal growing conditions and the complementary effects of intercrop species. The highest yields were obtained in 2020/21, with the highest seasonal rainfall total (1053 mm), while the lowest yields were observed in 2019/20 with the lowest seasonal rainfall total (495 mm). These results highlight the vulnerability of maize production to climate variability in semi-arid regions (Cairns and Prasanna, 2018; Tesfaye et al., 2018).

The significant interaction between season and strip cropping system

on maize grain yield indicates that the advantages of maize yield in maize-legume strip cropping systems depended on climatic conditions. For instance, Mz + vb improved yields in 2018/19 and 2020/21, likely due to velvet bean's vigorous growth, high nitrogen fixation, deep rooting, and weed suppression, which reduced competition for available resources, including moisture. In this study, velvet bean was planted four weeks after maize, allowing maize to have a starting position advantage in resource acquisition and rapid and dense ground cover, minimizing interspecific competition for the maize crop, and Disanayaka et al. (2024) and Droppelmann et al. (2017) support these results. However, these benefits were not consistent across all seasons, as excessive rainfall and management challenges reduced system performance. In contrast, dry spells lowered yields due to moisture stress, which constrained biomass production and reduced organic matter inputs (Midega et al., 2018). However, in the 2018/19 and 2020/21 seasons, Mz sole produced the highest yields, likely due to reduced interspecific competition for light and nutrients under favourable rainfall conditions. This aligns with studies by Lu et al. (2023), whose studies support the notion that under optimal rainfall and management conditions, Mz sole can outperform intercropped systems due to minimized competition and maximized resource use efficiency. However, in the 2019/20 and 2021/22 seasons, characterized by relatively lower productivity across all treatments, yields among the strip cropping systems

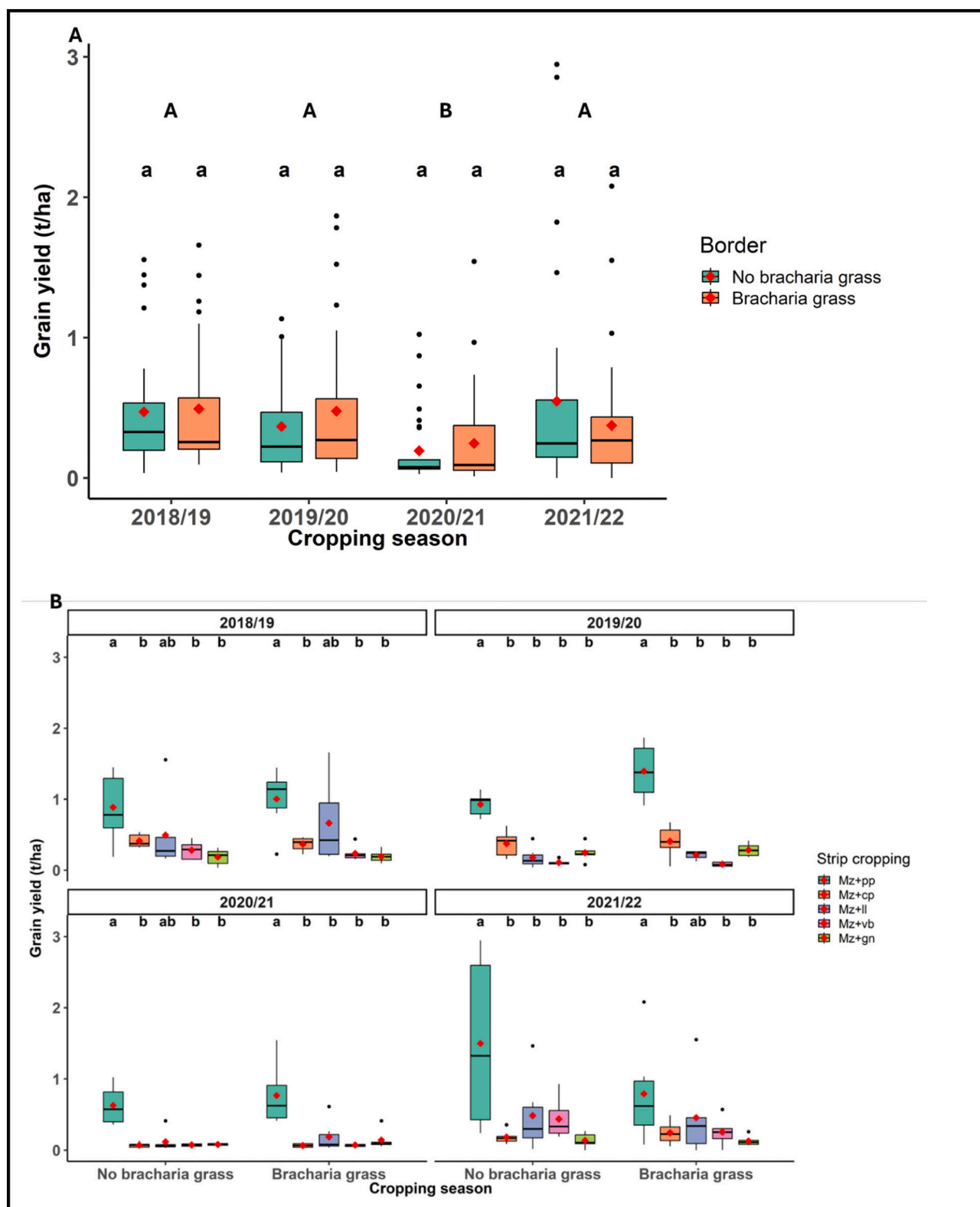


Fig. 6. Boxplots showing the influence of the interaction between season and border, and season, border, and strip cropping on legume grain yields. Codes: Mz + pp = Maize + pigeonpea, Mz + cp = Maize + cowpea, Mz + ll = Maize + lablab, Mz + vb = Maize + velvet bean, and Mz + gn = Maize + groundnut. The red diamond-shaped symbols indicate the mean legume grain yield of each factor. Treatments with different superscripted letters are significantly different at a 95 % confidence level: small letters for border and Capital letters for seasons (Fig. 6A).

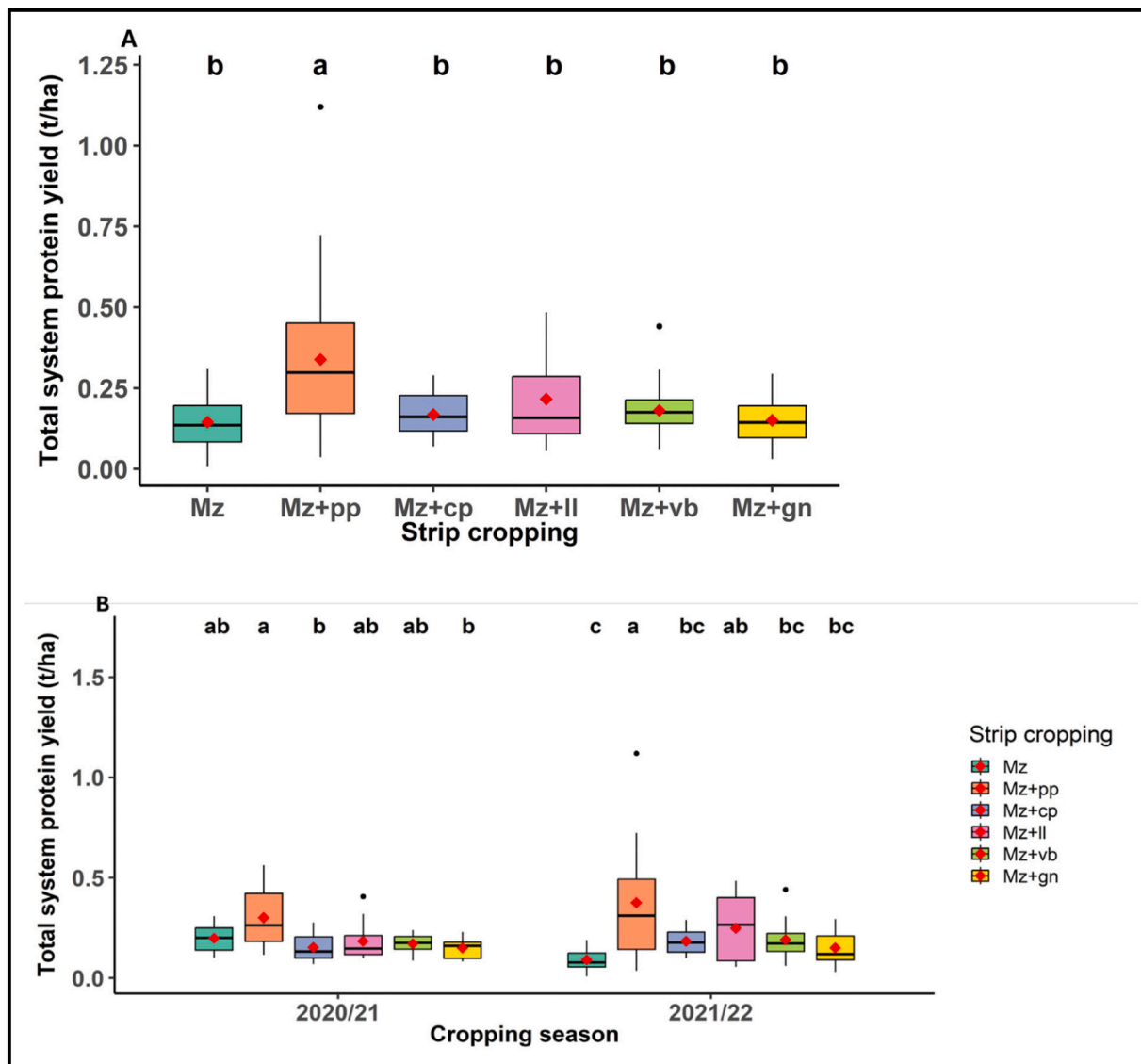


Fig. 7. Boxplots illustrating the influences of the strip cropping system and the interaction between season and strip cropping system on total system protein yield. Codes: Mz = sole maize, Mz + pp = Maize-pigeonpea, Mz + cp = Maize-cowpea, Mz + ll = Maize-lablab, Mz + vb = Maize-velvet bean, and Mz + gn = Maize-groundnut. The red diamond-shaped symbols denote the mean total system protein yield for each treatment (A) and interaction (B). Treatments with different superscripted letters are significantly different at a 95 % confidence level.

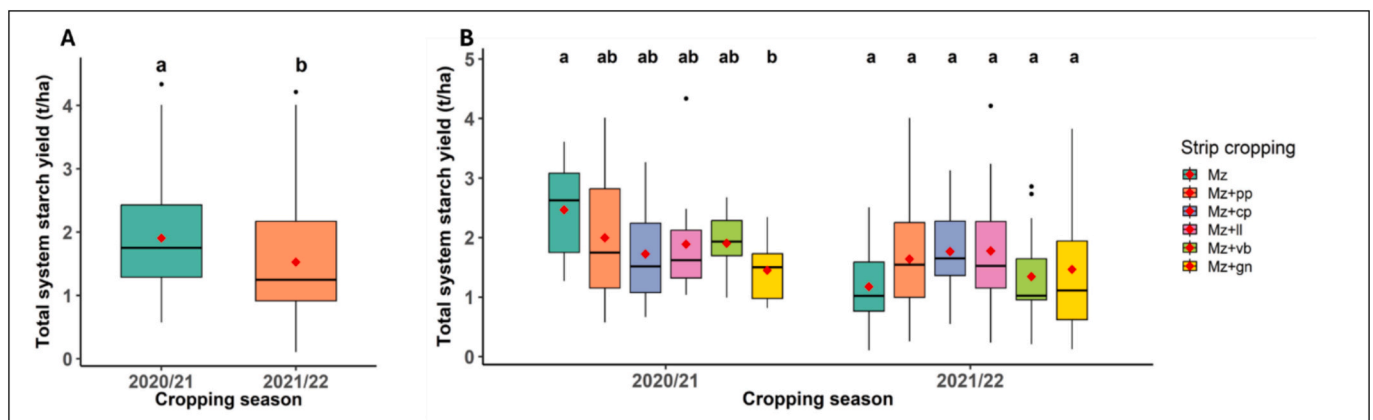


Fig. 8. Boxplots showing the effects of season and the interaction between season and strip cropping on total system starch yield. Codes: Mz = sole maize, Mz + pp = Maize + pigeonpea, Mz + cp = Maize + cowpea, Mz + ll = Maize + lablab, Mz + vb = Maize + velvet bean, and Mz + gn = Maize + groundnut. The red diamond-shaped symbols denote the mean total system starch (A and B). Treatments with different superscripted letters are significantly different at a 95 % confidence level.

were comparable, suggesting that the benefits of legume associations in stabilizing yield become more apparent under suboptimal or stress conditions.

Legume yields remained below 1 t ha⁻¹ across all seasons, reflecting low productivity under smallholder conditions with variable rainfall and soil fertility constraints, consistent with earlier studies (Bitew et al., 2022; Mupangwa et al., 2021). This additionally highlights the importance of both temporal and spatial factors in intercropping performance (Nassary, 2025; Wang et al., 2025a). Seasonal variability was evident, with the highest yields in 2018/19 and the lowest in 2020/21, emphasizing legumes' sensitivity to both drought and excess rainfall during flowering and pod filling. Among strip crops, pigeonpea consistently outperformed other legumes due to its slow initial growth, which reduces competition with maize, and its adaptive traits, including deep rooting, drought tolerance, extended growth duration, and nitrogen fixation (Frimpong et al., 2025; Khokhar et al., 2021). These traits enable pigeonpea to exploit residual moisture and nutrients more effectively than short-duration legumes, such as cowpea or groundnut, explaining its consistent yield advantage. In contrast, shallow-rooted species such as cowpea and groundnut are more susceptible to shading, root-zone competition, and pest pressures, which limit their performance (Mofokeng and Gerrano, 2021). Excess rainfall in the 2020/21 season suppressed legume productivity by impairing root growth and function (Nadeem et al., 2019; Striker and Colmer, 2016). Other studies, including Baxevasanos et al. (2017), reported legume genotypes to perform differently in sole cropping compared to strip and other intercropping systems, leading to changes in the performance ranking. Therefore, the selection of a particular genotype combination may also result in negative or positive yield effects (Raza et al., 2024; Renwick et al., 2020) and may require site-specific adaptation.

Furthermore, the observed interaction between season, border, and strip cropping on legume yields suggests that seasonal rainfall patterns were the dominant driver of legume yield variations, while *Brachiaria* border had a modulating effect on microclimate and soil moisture dynamics. High yields recorded in 2018/19 and 2021/22 corresponded with greater total rainfall and better intra-seasonal distribution, which are critical for legume flowering, pod formation, and grain filling. Adequate and well-distributed rainfall during these phenological stages enhances reproductive success and seed development in legumes (Chen et al., 2023). Conversely, the poor legume yields observed in the 2020/21 season likely reflect moisture stress during critical reproductive stages, which can severely impair pod set, seed development, and biological nitrogen fixation. During flowering and pod filling, legumes are particularly sensitive to water deficits, and even short-term drought stress can lead to flower abortion, incomplete pod formation, and reduced translocation of assimilates to developing seeds (Khatun et al., 2021).

The consistently superior performance of pigeonpea across all seasons is attributable to its deep-rooting system, drought tolerance, and extended growth duration, allowing it to exploit residual soil moisture after the cessation of rains (Musokwa and Mafongoya, 2020). Short-duration legumes such as cowpea and lablab, while beneficial for early ground cover, were more sensitive to water stress and thus exhibited stronger yield fluctuations across seasons (Khatun et al., 2021; Poudel et al., 2025). Although the *Brachiaria* border did not significantly increase yields, its role in enhancing soil structure, water infiltration, and reducing runoff (Diop et al., 2022), likely contributed to maintaining relatively stable yields under variable rainfall. Over time, these borders could offer cumulative benefits through improved soil organic matter and moisture retention (Ruggieri et al., 2020), supporting the long-term sustainability of maize-legume strip cropping systems in semi-arid regions.

4.4. Strip cropping systems effects on total system protein and starch yields

Strip cropping systems and cropping seasons significantly influenced total system protein and starch yields, with outcomes largely shaped by the growth habits, nutritional composition of the legume species, and prevailing environmental conditions (Juventia et al., 2022). Favourable environmental conditions may influence total system starch and protein synthesis. For instance, moderate temperature and moisture in the temperate regions of Romania supported higher system protein (14.9 %) and starch yields (Szulec et al., 2020).

In this study, Mz + pp strip cropping produced the highest total system protein yields compared to other strip crops. This advantage is likely due to the high productivity of the system and pigeonpea's capacity for biological nitrogen fixation, which enhances soil N availability, a key determinant of protein accumulation (Markos and Yoseph, 2024). Studies have shown that pigeonpea can increase system-level protein yield by up to 65 % through improved N supply to both the intercrop and subsequent crops (Chimonyo et al., 2019; Witcombe and Tiemann, 2022). Additionally, the spatial arrangement of Mz + pp may have optimized resource use efficiency, reducing interspecific competition and allowing greater allocation of assimilates toward protein synthesis (García-Lara and Serna-Saldivar, 2019; Juventia et al., 2022).

In contrast, Mz sole consistently recorded the lowest protein yields, emphasizing the importance of integrating N-fixing legumes into cereal-based systems to improve nutritional productivity. Seasonal variation further influenced treatment performance, yet Mz + pp maintained significantly higher protein yields in both 2020/21 and 2021/22, highlighting its resilience under variable rainfall conditions. Similar patterns have been reported in other recent studies, where pigeonpea intercropping improved protein productivity through sustained nitrogen inputs and reduced competition during maize's early growth stages (Chimonyo et al., 2023).

Season and season × border interactions significantly affected starch yield. The decline in starch yield from 2020/21 to 2021/22 highlights the strong sensitivity of carbohydrate accumulation to climatic conditions. The findings concur with studies by Martínez et al. (2017) and Wang et al. (2023). High starch yields in Mz sole during 2020/21 align with the crop's carbohydrate dominance and reduced competition compared to intercropping systems, as supported by Al-Naggar et al. (2020) and Maitra et al. (2024). However, the lack of significant treatment differences in 2021/22 suggests that under moderate rainfall and potentially greater stress conditions, treatment effects on starch allocation become less distinct. Previous studies have similarly observed that maize starch accumulation is closely tied to water availability and environmental stress, which can override the effects of management systems (Han et al., 2025; Huang et al., 2023). The relatively higher starch in Mz + ll, Mz + cp, and Mz + pp in 2021/22, although not statistically significant, suggests that strip crops with complementary traits may help stabilize maize carbohydrate yields under challenging conditions.

4.5. Constraints and appropriateness of strip cropping system for smallholder farming systems

Although the strip cropping system yielded benefits in this study, including improvements in some soil nutrients and grain and nutritional yields, the advantages are not uniform and are sensitive to seasonal variation. The system faced several challenges that warrant further research to better align cropping designs with farmers' practical needs and preferences. The challenges included: (i) methodological limitations related to site soil type variability — the absence of a quantitative baseline of soil properties before 2020/21 hindered a detailed evaluation of long-term soil effects, hence interpretations should be focused on observed changes over the past two seasons rather than cumulative over the full trial period across farmers. Future studies should incorporate

comprehensive initial soil profiling to enhance understanding of soil-treatment interactions; (ii) long-term monitoring of strip cropping effects — trials lasting fewer than five seasons may not fully capture the stability or resilience of strip cropping systems under varying climatic conditions. Therefore, longer-term trials are essential to evaluate the sustainability of such systems, yield stability, and soil quality dynamics over time; (iii) limited measurement of underlying processes — although yield improvements were observed, the study did not quantify key processes that may have caused such improvements. Further research is needed to assess root distribution, microbial mediation, biological nitrogen fixation, soil moisture retention, and weed suppression, which could not be conducted due to funding constraints. Future research should incorporate these measurements to gain a deeper understanding of why certain cropping combinations perform better under specific conditions; (iv) finally, future research should test how to optimize border width, species, and management, and examine economic trade-offs for labour, input costs, and use of such resources in mixed crop/livestock systems.

5. Conclusions

This study aimed to understand the effects of maize-legume strip cropping systems on crop productivity, soil quality, and nutrition under smallholder farming conditions in Zimbabwe. Despite seasonal variability, the integration of legumes, particularly pigeonpea, consistently improved total system protein yield compared to sole maize, highlighting the value of long-duration, nitrogen-fixing legumes in boosting soil N and grain nutritional quality. The 2020/21 season, with above-average rainfall, supported higher yields of protein and starch, while the drier 2021/22 season led to reductions, highlighting the sensitivity of these systems to climate variability. Although sole maize produced higher starch yields under favourable rainfall, intercropping with legumes offers long-term soil fertility benefits that may offset short-term yield trade-offs.

Soil nutrient analysis revealed that specific strip cropping systems, notably maize intercropped with cowpea and groundnuts, improved key fertility indicators by enhancing pH, K, and SOC, which are critical in low-input smallholder contexts. These improvements highlight the role of legume-based strip cropping in promoting a more balanced and fertile soil environment, thereby supporting sustainable crop production.

Yield gaps among systems were driven by variations in soil nutrient availability and seasonal rainfall patterns, emphasizing the need for strategic species selection and adaptive management. While maize-legume strip cropping is relatively new in Zimbabwe, the results affirm its potential to improve soil parameters like K and food and nutrition security. Long-term evaluations are therefore warranted to fully capture the agronomic and ecological benefits of this approach in smallholder farming systems.

Overall, integrating suitable legume species such as cowpea, pigeonpea, velvet bean, or groundnut into maize-based strip cropping systems can enhance the system's sustainability under variable rainfall conditions. These findings reinforce the potential of maize-legume strip cropping as a viable strategy for stabilizing maize productivity of smallholder farming systems in southern Africa.

CRedit authorship contribution statement

Connie Madembo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Frédéric Baudron:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Arnold B. Mashigaidze:** Writing – review & editing, Supervision. **Chrispen Murungweni:** Writing – review & editing, Supervision. **Courage Bangira:** Writing – review & editing, Supervision. **Tarirai Muoni:** Writing – review & editing. **Christian Thierfelder:** Writing – review & editing, Supervision,

Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare they have not used any of the Generative AI tools in creating this article.

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Declaration of competing interest

The authors declare no conflict of interest exists.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aoas.2025.100401>.

References

- Abdoul-Karim, T.D., Abdel-Kader, A.S., Soulé, M., Sareye, A., Sanoussi, A., Yacoubou, B., 2025. Short-term effects of cowpea (*Vigna unguiculata* [L.] Walp) cultivation and mineral fertilization on soil bacterial abundance and chemical properties. *Environ. Challenges*, 101292. <https://doi.org/10.1016/j.envc.2025.101292>.
- Adeyeye, S.A.O., Adebayo-Oyetoro, A.O., Tiamiyu, H.K., 2017. Poverty and malnutrition in Africa: a conceptual analysis. *Nutr. Food Sci.* 47, 754–764. <https://doi.org/10.1108/NFS-02-2017-0027>.
- Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M.R.A.F., Rajpoot, S.K., Choudhary, A.K., 2025. Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review. *Front. Sustain. Food Syst.* 9, 1527256. <https://doi.org/10.3389/fsufs.2025.1527256>.
- Al-Naggar, A., Bakry, B., Nassar, S., 2020. Maximizing maize grain, protein, oil and starch yields by using high plant density and stress tolerant genotype. *Asian J. Plant Sci.* 20, 91–101. <https://doi.org/10.3923/ajps.2021.91.101>.
- Andrews, E.M., Kassama, S., Smith, E.E., Brown, P.H., Khalsa, S.D.S., 2021. A review of potassium-rich crop residues used as organic matter amendments in tree crop agroecosystems. *Agriculture* 11, 580. <https://doi.org/10.3390/agriculture11070580>.
- Arunrat, N., Kongsurakan, P., Sreenonchai, S., Hatano, R., 2020. Soil organic carbon in sandy paddy fields of Northeast Thailand: a review. *Agronomy* 10, 1061. <https://doi.org/10.3390/agronomy10081061>.
- Balpande, S., Sarap, P., Ghodpage, R., 2016. Effect of potassium and sulphur on nutrient uptake, yield and quality of pigeon pea (*Cajanus cajan*). *Agric. Sci. Dig. Res. J.* 36, 323–325. <https://doi.org/10.18805/asd.v36i4.6476>.
- Barberis, E., Ajmone Marsan, F., Scalenghe, R., Lammers, A., Schwertmann, U., Edwards, A., Maguire, R., Wilson, M., Delgado, A., Torrent, J., 1995. European soils overfertilized with phosphorus: part 1. Basic properties. *Fertil. Res.* 45, 199–207. <https://doi.org/10.1007/BF00748590>.
- Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>.
- Baudron, F., Sims, B., Justice, S., Kahan, D.G., Rose, R., Mkomwa, S., Kaumbutho, P., Sariah, J., Nazare, R., Moges, G., 2015. Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement. *Food Secur.* 7, 889–904. <https://doi.org/10.1007/s12571-015-0476-3>.
- Baudron, F., Zaman-Allah, M.A., Chaipa, I., Chari, N., Chinwada, P., 2019. Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* JE Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe. *Crop Prot.* 120, 141–150. <https://doi.org/10.1016/j.cropro.2019.01.028>.
- Baxevanos, D., Tsialtas, I.T., Vlachostergios, D.N., Hadjigeorgiou, I., Dordas, C., Lithourgidis, A., 2017. Cultivar competitiveness in pea-oat intercrops under Mediterranean conditions. *Field Crop Res.* 214, 94–103. <https://doi.org/10.1016/j.fcr.2017.08.024>.

- Bitew, Y., Derebe, B., Worku, A., Chakelie, G., 2022. Maize-legume systems under conservation agriculture. *Agron. J.* 114, 173–186. <https://doi.org/10.1002/ajg2.20925>.
- Bolinder, M.A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., Kätterer, T., 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitig. Adapt. Strateg. Glob. Chang.* 25, 929–952. <https://doi.org/10.1007/s11027-020-09916-3>.
- Bouhenache, A., Lashermes, G., Clivot, H., Recous, S., Chikowo, R., Shumba, A., Mazungunye, H., Matimba, E., Alavoine, G., Delfosse, O., 2025. Intra-seasonal rainfall patterns and extremes drive maize productivity and nitrogen use in sub-humid Zimbabwe. *Field Crop Res.* 334, 110126. <https://doi.org/10.1016/j.fcr.2025.110126>.
- Cairns, J.E., Prasanna, B.M., 2018. Developing and deploying climate-resilient maize varieties in the developing world. *Curr. Opin. Plant Biol.* 45, 226–230. <https://doi.org/10.1016/j.cpb.2018.05.004>.
- Chen, M., Zhang, T.-L., Hu, C.-G., Zhang, J.-Z., 2023. The role of drought and temperature stress in the regulation of flowering time in annuals and perennials. *Agronomy* 13, 3034. <https://doi.org/10.3390/agronomy13123034>.
- Chimonyo, V.G.P., Snapp, S.S., Chikowo, R., 2019. Grain legumes increase yield stability in maize based cropping systems. *Crop Sci.* 59, 1222–1235. <https://doi.org/10.2135/cropsci2018.09.0532>.
- Chimonyo, V.G.P., Govender, L., Nyathi, M., Scheelbeek, P.F.D., Choruma, D.J., Mustafa, M., Massawe, F., Slotow, R., Modi, A.T., Mabhaudhi, T., 2023. Can cereal-legume intercrop systems contribute to household nutrition in semi-arid environments: a systematic review and meta-analysis. *Front. Nutr.* 10, 1060246. <https://doi.org/10.3389/fnut.2023.1060246>.
- Dimande, P., Arrobas, M., Rodrigues, M.A., 2024. Intercropped maize and cowpea increased the land equivalent ratio and enhanced crop access to more nitrogen and phosphorus compared to cultivation as sole crops. *Sustainability* 16, 1440. <https://doi.org/10.3390/su16041440>.
- Diop, M., Chirinda, N., Beniaich, A., El Gharous, M., El Mejahed, K., 2022. Soil and water conservation in Africa: state of play and potential role in tackling soil degradation and building soil health in agricultural lands. *Sustainability* 14, 13425. <https://doi.org/10.3390/su142013425>.
- Dissanayaka, D., Uduumani, S., Nuwarapaksha, T., Atapattu, A.J., 2024. Harnessing the potential of *Mucuna* cover cropping: a comprehensive review of its agronomic and environmental benefits. *Circ. Agric. Syst.* 4. <https://doi.org/10.48130/cas-0024-0001>.
- Droppelmann, K.J., Snapp, S.S., Waddington, S.R., 2017. Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa. *Food Secur.* 9, 133–150. <https://doi.org/10.1007/s12571-016-0636-0>.
- Eckert, D., Sims, J.T., 1995. Recommended soil pH and lime requirement tests. *Recomm. Soil Test. Proced. Northeast. U. S. Northeast Reg. Bull.* 493, 11–16.
- Fisher, M., Abate, T., Lunduka, R.W., Asnake, W., Alemayehu, Y., Madulu, R.B., 2015. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: determinants of adoption in eastern and southern Africa. *Clim. Chang.* 133, 283–299. <https://doi.org/10.1007/s10584-015-1459-2>.
- Franzluebbers, A.J., Wendroth, O., Creamer, N.G., Feng, G.G., 2020. Focusing the future of farming on agroecology. *Agric. Environ. Lett.* 5, e20034. <https://doi.org/10.1002/acl2.20034>.
- Frimpong, F., Danquah, E.O., Amponsah, S.K., Frimpong, T., Adu, J., Danquah, F.O., Amengor, N.E., Amankwa-Yeboah, P., 2025. Diversifying cropping systems to enhance productivity using agroforestry trees: a case study of maize-pigeon pea intercropping in Ghana. *Explora Environ. Resour.*, 025130026 <https://doi.org/10.36922/EER025130026>.
- Fu, Z., Chen, P., Zhang, X., Du, Q., Zheng, B., Yang, H., Luo, K., Lin, P., Li, Y., Pu, T., 2023. Maize-legume intercropping achieves yield advantages by improving leaf functions and dry matter partition. *BMC Plant Biol.* 23, 438. <https://doi.org/10.1186/s12870-023-04408-3>.
- García-Lara, S., Serna-Saldivar, S.O., 2019. Corn history and culture. In: *Corn*, pp. 1–18. <https://doi.org/10.1016/B978-0-12-811971-6.00001-2>.
- Haarhoff, S.J., Kotzé, T.N., Swanepoel, P.A., 2020. A prospectus for sustainability of rainfed maize production systems in South Africa. *Crop Sci.* 60, 14–28. <https://doi.org/10.1002/csc2.20103>.
- Han, Y., Wei, S., Xu, A., Wei, C., 2025. Development and properties of starches in vitreous and flourey endosperm of maize. *Agriculture* 15, 1978. <https://doi.org/10.3390/agriculture15181978>.
- Hou, R., Tomalin, L.E., Suárez-Fariñas, M., 2021. cosinoRmixedeffects: an R package for mixed-effects cosinor models. *BMC Bioinformatics* 22, 553. <https://doi.org/10.1186/s12859-021-04463-3>.
- Huang, C., Qin, A., Gao, Y., Ma, S., Liu, Z., Zhao, B., Ning, D., Zhang, K., Gong, W., Sun, M., 2023. Effects of water deficit at different stages on growth and ear quality of waxy maize. *Front. Plant Sci.* 14, 1069551. <https://doi.org/10.3389/fpls.2023.1069551>.
- Iqbal, N., Hussain, S., Ahmed, Z., Yang, F., Wang, X., Liu, W., Yong, T., Du, J., Shu, K., Yang, W., 2019. Comparative analysis of maize-soybean strip intercropping systems: a review. *Plant Prod. Sci.* 22, 131–142. <https://doi.org/10.1080/1343943X.2018.1541137>.
- Islam, M., Cheng, M., Kumar, U., Maniruzzaman, M., Nasreen, S., Haque, M., Jahiruddin, M., Bell, R., Jahangir, M., 2023. Conservation agriculture in intensive rice cropping reverses soil potassium depletion. *Nutr. Cycl. Agroecosyst.* 125, 437–451. <https://doi.org/10.1007/s10705-023-10261-5>.
- Jagtap, S., Trollman, H., Trollman, F., García-García, G., Parra-López, C., Duong, L., Martindale, W., Muneke, P.E., Lorenzo, J.M., Hdaifeh, A., 2022. The Russia-Ukraine conflict: its implications for the global food supply chains. *Foods* 11, 2098. <https://doi.org/10.3390/foods11142098>.
- Juventia, S.D., Norén, I.L.S., Van Apeldoorn, D.F., Ditzler, L., Rossing, W.A., 2022. Spatio-temporal design of strip cropping systems. *Agric. Syst.* 201, 103455. <https://doi.org/10.1016/j.agsy.2022.103455>.
- Juventia, S.D., van Apeldoorn, D.F., Faber, H., Rossing, W.A., 2025. From sole crops to strip cropping: decision rules of frontrunner farmers in The Netherlands. *PLoS One* 20, e0329133. <https://doi.org/10.1371/journal.pone.0329133>.
- Kebede, Y., Baudron, F., Bianchi, F., Tittone, P., 2018. Unpacking the push-pull system: assessing the contribution of companion crops along a gradient of landscape complexity. *Agric. Ecosyst. Environ.* 268, 115–123. <https://doi.org/10.1016/j.agee.2018.09.012>.
- Khatun, M., Sarkar, S., Era, F.M., Islam, A.M., Anwar, M.P., Fahad, S., Datta, R., Islam, A., 2021. Drought stress in grain legumes: effects, tolerance mechanisms and management. *Agronomy* 11, 2374. <https://doi.org/10.3390/agronomy11122374>.
- Khokhar, A., Yousuf, A., Singh, M., Sharma, V., Sandhu, P.S., Chary, G.R., 2021. Impact of land configuration and strip-intercropping on runoff, soil loss and crop yields under rainfed conditions in the Shivalik foothills of north-west, India. *Sustainability* 13, 6282. <https://doi.org/10.3390/su13116282>.
- Kihara, J., Bolo, P., Kinyua, M., Nyawira, S.S., Sommer, R., 2020. Soil health and ecosystem services: lessons from sub-Saharan Africa (SSA). *Geoderma* 370, 114342. <https://doi.org/10.1016/j.geoderma.2020.114342>.
- Kuznetsova, A., Brockhoff, P.B., Christensen, R.H., 2017. lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82, 1–26. <https://doi.org/10.18637/jss.v082.i13>.
- Liu, G., Yang, Y., Liu, W., Guo, X., Xue, J., Xie, R., Ming, B., Wang, K., Hou, P., Li, S., 2020. Leaf removal affects maize morphology and grain yield. *Agronomy* 10, 269. <https://doi.org/10.3390/agronomy10020269>.
- Lonnie, M., Hooker, E., Brunstrom, J.M., Corfe, B.M., Green, M.A., Watson, A.W., Williams, E.A., Stevenson, E.J., Penson, S., Johnstone, A.M., 2018. Protein for life: review of optimal protein intake, sustainable dietary sources and the effect on appetite in ageing adults. *Nutrients* 10, 360. <https://doi.org/10.3390/nu10030360>.
- Lu, J., Dong, Q., Lan, G., He, Z., Zhou, D., Zhang, H., Wang, X., Liu, X., Jiang, C., Zhang, Z., 2023. Row ratio increasing improved light distribution, photosynthetic characteristics, and yield of peanut in the maize and peanut strip intercropping system. *Front. Plant Sci.* 14, 1135580. <https://doi.org/10.3389/fpls.2023.1135580>.
- Ma, W., Tang, S., Dengzeng, Z., Zhang, D., Zhang, T., Ma, X., 2022. Root exudates contribute to belowground ecosystem hotspots: a review. *Front. Microbiol.* 13, 937940. <https://doi.org/10.3389/fmicb.2022.937940>.
- Madembo, C., Mhlamba, B., Thierfelder, C., 2020. Productivity or stability? Exploring maize-legume intercropping strategies for smallholder conservation agriculture farmers in Zimbabwe. *Agric. Syst.* 185, 102921. <https://doi.org/10.1016/j.agsy.2020.102921>.
- Maitra, S., Sain, S., Sairam, M., Shankar, T., Ray, S., Banerjee, M., Malik, G., 2024. Impact of Rabi maize-legume intercropping system on growth, yield and crop competition in maize. *Res. Crops* 25, 409–415. <https://doi.org/10.31830/2348-7542.2024.ROC-1093>.
- Makate, C., Wang, R., Makate, M., Mango, N., 2016. Crop diversification and livelihoods of smallholder farmers in Zimbabwe: adaptive management for environmental change. *SpringerPlus* 5, 1135. <https://doi.org/10.1186/s40064-016-2802-4>.
- Markos, D., Yoseph, T., 2024. Revitalizing maize production through managing biological N fixation, soil acidification and nitrous oxide emission from legumes in tropics. *Afr. J. Environ. Sci. Technol.* 18, 21–40. <https://doi.org/10.5897/AJEST2023.3245>.
- Martínez, R.D., Cirilo, A.G., Cerrudo, A., Andrade, F.H., Reinoso, L., Valentinuz, O.R., Balbi, C.N., Izquierdo, N.G., 2017. Changes of starch composition by postflowering environmental conditions in kernels of maize hybrids with different endosperm hardness. *Eur. J. Agron.* 86, 71–77. <https://doi.org/10.1016/j.eja.2017.04.001>.
- Mbanjwa, V.E., Muchaonyerwa, P., Hughes, J.C., 2023. Total organic carbon, aluminium and iron in bulk samples and aggregate size fractions of a sandy clay loam humic soil under sugarcane relative to native forest in northern KwaZulu-Natal, South Africa. *Heliyon* 9. <https://doi.org/10.1134/S1064229307060063>.
- Mhlamba, B., Cheesman, S., Maasdorp, B., Mupangwa, W., Thierfelder, C., 2015. Contribution of cover crops to the productivity of maize-based conservation agriculture systems in Zimbabwe. *Crop Sci.* 55, 1791–1805. <https://doi.org/10.2135/cropsci2014.11.0796>.
- Midega, C.A., Pittchar, J.O., Pickett, J.A., Hailu, G.W., Khan, Z.R., 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (JE Smith), in maize in East Africa. *Crop Prot.* 105, 10–15. <https://doi.org/10.1016/j.cropro.2017.11.003>.
- Mofokeng, M.A., Gerrano, A.S., 2021. Efforts in breeding cowpea for aphid resistance: a review. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 71, 489–497. <https://doi.org/10.1080/09064710.2021.1923797>.
- Mulvaney, R.L., 1996. Nitrogen—inorganic forms. *Methods Soil Anal. Pt. 3 Chem. Methods* 5, 1123–1184. <https://doi.org/10.2136/sssabookser5.3.c38>.
- Mupangwa, W., Nyagumbo, I., Liben, F., Chipindu, L., Craufurd, P., Mkuhlani, S., 2021. Maize yields from rotation and intercropping systems with different legumes under conservation agriculture in contrasting agro-ecologies. *Agric. Ecosyst. Environ.* 306, 107170. <https://doi.org/10.1016/j.agee.2020.107170>.
- Murage, A., Midega, C., Pittchar, J., Pickett, J., Khan, Z., 2015. Determinants of adoption of climate-smart push-pull technology for enhanced food security through integrated pest management in eastern Africa. *Food Secur.* 7, 709–724. <https://doi.org/10.1007/s12571-015-0454-9>.
- Musidzaramba, T.J., Mvumi, B.M., Nyanga, L.K., Kadzere, I., Kiboi, M., Mahlangu, M., Chingoma, G., Mazula, M., Macheke, L., 2025. Nutritional profile and food safety of raw and value-added food products of sorghum and millets in sub-Saharan Africa

- and South Asia. *Cogent Food Agric.* 11, 2461628. <https://doi.org/10.1080/23311932.2025.2461628>.
- Musokwa, M., Mafongoya, P., 2020. Pigeonpea yield and water use efficiency: a savior under climate change-induced water stress. *Agronomy* 11, 5. <https://doi.org/10.3390/agronomy11010005>.
- Nacinovic, M.G.G., Mahler, C.F., de Oliveira Marques, M.C., de Macedo, J.R., da Silva Melo, A., Souza, G.O., Borges, R.C., 2024. Comparison Between Vetiver and *Brachiaria* Grass in Erosion Control in Tropical Climate. <https://doi.org/10.37256/scs.5220244925>.
- Nadeem, M., Li, J., Yahya, M., Sher, A., Ma, C., Wang, X., Qiu, L., 2019. Research progress and perspective on drought stress in legumes: a review. *Int. J. Mol. Sci.* 20, 2541. <https://doi.org/10.3390/ijms20102541>.
- Nakashima, K., Yanagihara, S., Muranaka, S., Oya, T., 2022. Development of sustainable technologies to increase agricultural productivity and improve food security in Africa. *Jpn. Agric. Res. Q.* 56, 7–18. <https://doi.org/10.6090/jarq.56.7>.
- NASA POWER | Data Access Viewer (DAV), 2023 [WWW document]. URL <https://power.larc.nasa.gov/data-access-viewer/>.
- Nassary, E.K., 2025. Benefits of common bean intercropping with maize are independent of altitudinal gradients in the northern highlands of Tanzania. *Curr. Res. Prog. Agric. Sci.* 8, 39–66. <https://doi.org/10.9734/bpi/crpas/v8/4051>.
- Nchanji, E.B., Lutomia, C.K., 2021. COVID-19 challenges to sustainable food production and consumption: future lessons for food systems in eastern and southern Africa from a gender lens. *Sustainable Prod. Consumption* 27, 2208–2220. <https://doi.org/10.1016/j.spc.2021.05.016>.
- Nciizah, T., Nciizah, E., Mubekaphi, C., Nciizah, A.D., 2021. Role of Small Grains in Adapting to Climate Change: Zvishavane District, Zimbabwe. https://doi.org/10.1007/978-3-030-42091-8_254-1.
- Ndhlela, T., Herselman, L., Magorokosho, C., Setimela, P., Mutimaamba, C., Labuschagne, M., 2014. Genotype × environment interaction of maize grain yield using AMMI biplots. *Crop Sci.* 54, 1992–1999. <https://doi.org/10.2135/cropsci2013.07.0448>.
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. *Methods Soil Anal. Pt. 3 Chem. Methods* 5, 961–1010. <https://doi.org/10.2136/sssabooks5.3.c34>.
- Netthisinghe, A.M., Galloway, H.O., Agga, G.E., Gunter, P.A., Sistani, K.R., 2023. Effects of cropping systems on soil physicochemical properties and abundances and spatial distributions of nitrogen-cycling bacteria. *Agronomy* 13, 1461. <https://doi.org/10.3390/agronomy13061461>.
- Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C.R., Muchara, B., Karuaihe, S. T., Mpandeli, S., 2020. Climate change impacts on water and agriculture sectors in Southern Africa: threats and opportunities for sustainable development. *Water* 12, 2673. <https://doi.org/10.3390/w12102673>.
- Nyagumbo, I., Mupangwa, W., Chipindu, L., Rusinamhodzi, L., Craufurd, P., 2020. A regional synthesis of seven-year maize yield responses to conservation agriculture technologies in Eastern and Southern Africa. *Agric. Ecosyst. Environ.* 295, 106898. <https://doi.org/10.1016/j.agee.2020.106898>.
- Nyakudya, I.W., Stroosnijder, L., 2015. Conservation tillage of rainfed maize in semi-arid Zimbabwe: a review. *Soil Tillage Res.* 145, 184–197. <https://doi.org/10.1016/j.still.2014.09.003>.
- Nyakurwa, C., Gasura, E., Mabasa, S., 2017. Potential for quality protein maize for reducing protein undernutrition in maize dependent Sub-Saharan African countries: a review. *Afr. Crop. Sci. J.* 25, 521–537. <https://doi.org/10.4314/acscj.v25i4.9>.
- Nyamayevu, D., Nyagumbo, I., Liang, W., Li, R., Silva, J.V., 2024. Grain and nutritional yield merits of sustainable intensification through maize-legume rotations in land constrained smallholder farms of Malawi. *Field Crop Res.* 318, 109565. <https://doi.org/10.1016/j.fcr.2024.109565>.
- Nyoni, N.M., Grab, S., Archer, E., Hetem, R., 2022. Perceived impacts of climate change on rural poultry production: a case study in Limpopo Province, South Africa. *Clim. Dev.* 14, 389–397. <https://doi.org/10.1080/17565529.2021.1929803>.
- Phiri, A.T., Njira, K.O.W., 2023. Grain legume-based cropping systems' effects on soil organic carbon and nutrient dynamics. *Agric. Res.* 12, 45–52. <https://doi.org/10.1007/s40003-022-00619-6>.
- Poudel, S., Valsala Sankarapillai, L., Sivarathri, B.S., Hosahalli, V., Harkess, R.L., Bheemanahalli, R., 2025. Characterization of cowpea genotypes for traits related to early-season drought tolerance. *Agriculture* 15, 1075. <https://doi.org/10.3390/agriculture15101075>.
- R Core Team. A language and environment for statistical computing (Version 4.4.2) [Computer software]. R Foundation for Statistical Computing. <https://www.r-project.org/>.
- Raza, M.A., Din, A.M.U., Shah, G.A., Zhiqi, W., Feng, L.Y., Gul, H., Yasin, H.S., ur Rahman, M.S., Juan, C., Liang, X., 2024. Legume choice and planting configuration influence intercrop nutrient and yield gains through complementarity and selection effects in legume-based wheat intercropping systems. *Agric. Syst.* 220, 104081. <https://doi.org/10.1016/j.agry.2024.104081>.
- Rehman, S. ur, Ijaz, S.S., Din, A.M.U., Al-Dosary, M.A., Ansar, M., Fatima, S., Siddiqi, A., Ashraf, M.N., Haider, I., Junaid, M.B., 2025. Combined effects of reduced tillage and strip intercropping on soil carbon sequestration in semi-arid environment. *J. Soil Sci. Plant Nutr.* 1–16. <https://doi.org/10.1007/s42729-025-02324-z>.
- Renwick, L.L., Kimaro, A.A., Hafner, J.M., Rosenstock, T.S., Gaudin, A.C., 2020. Maize-pigeonpea intercropping outperforms monocultures under drought. *Front. Sustain. Food Syst.* 4, 562663. <https://doi.org/10.3389/fsufs.2020.562663>.
- Ruggieri, A.C., Cardoso, A. da S., Ongaratto, F., Casagrande, D.R., Barbero, R.P., Brito, L. de F., Azenha, M.V., Oliveira, A.A., Koscheck, J.F.W., Reis, R.A., 2020. Grazing intensity impacts on herbage mass, sward structure, greenhouse gas emissions, and animal performance: analysis of *Brachiaria* pastureland. *Agronomy* 10, 1750. <https://doi.org/10.3390/agronomy10111750>.
- Rusinamhodzi, L., Dahlin, S., Corbeels, M., 2016. Living within their means: reallocation of farm resources can help smallholder farmers improve crop yields and soil fertility. *Agric. Ecosyst. Environ.* 216, 125–136. <https://doi.org/10.1016/j.agee.2015.09.033>.
- Shonhe, T., 2022. The politics of mechanisation in Zimbabwe: tractors, accumulation and agrarian change. *J. Peasant Stud.* 49, 179–199. <https://doi.org/10.1080/03066150.2021.1918114>.
- Siddiqui, F., Salam, R.A., Lassi, Z.S., Das, J.K., 2020. The intertwined relationship between malnutrition and poverty. *Front. Public Health* 8, 453. <https://doi.org/10.3389/fpubh.2020.00453>.
- da Silva, L.C.M., Avanzi, J.C., Peixoto, D.S., Merlo, M.N., Borghi, E., de Resende, A.V., Acuna-Guzman, S.F., Silva, B.M., 2021. Ecological intensification of cropping systems enhances soil functions, mitigates soil erosion, and promotes crop resilience to dry spells in the Brazilian Cerrado. *Int. Soil Water Conserv. Res.* 9, 591–604. <https://doi.org/10.1016/j.iswcr.2021.06.006>.
- Sirisuntornlak, N., Ullah, H., Sonjaroorn, W., Anusontornperm, S., Ariroh, W., Datta, A., 2021. Interactive effects of silicon and soil pH on growth, yield and nutrient uptake of maize. *Silicon* 13, 289–299. <https://doi.org/10.1007/s12633-020-00427-z>.
- Soropa, G., Nyamangara, J., Nyakatawa, E.Z., 2019. Nutrient status of sandy soils in smallholder areas of Zimbabwe and the need to develop site-specific fertiliser recommendations for sustainable crop intensification. *South Afr. J. Plant Soil* 36, 149–151. <https://doi.org/10.1080/02571862.2018.1517901>.
- Striker, G.G., Colmer, T.D., 2016. Flooding Tolerance of Forage Legumes. <https://doi.org/10.1093/jxb/erw239>.
- Sujatha, S., Tanuja, S., Hima Bindu, K., Kalaivanan, D., 2024. Biomass accumulation, soil fertility and energy use in seed crop systems of velvet bean (*Mucuna pruriens* L.). *Commun. Soil Sci. Plant Anal.* 55, 3263–3285. <https://doi.org/10.1080/00106324.2024.2391463>.
- Summer, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. *Methods Soil Anal. Pt. 3 Chem. Methods* 5, 1201–1229. <https://doi.org/10.2136/sssabooks5.3.c40>.
- Szulc, P., Ambroży-Deregowska, K., Mejza, I., Kobus-Cisowska, J., Ligaj, M., 2020. The role of agrotechnical factors in shaping the protein yield of maize (*Zea mays* L.). *Sustainability* 12, 6833. <https://doi.org/10.3390/su12176833>.
- Teng, J., Hou, R., Dungait, J.A., Zhou, G., Kuzaykov, Y., Zhang, J., Tian, J., Cui, Z., Zhang, F., Delgado-Baquerizo, M., 2024. Conservation agriculture improves soil health and sustains crop yields after long-term warming. *Nat. Commun.* 15, 8785. <https://doi.org/10.1038/s41467-024-53169-6>.
- Tesfaye, K., Kruseman, G., Cairns, J.E., Zaman-Allah, M., Wegary, D., Zaidi, P., Boote, K. J., Erenstein, O., 2018. Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments. *Clim. Risk Manag.* 19, 106–119. <https://doi.org/10.1016/j.crm.2017.10.001>.
- Thien, S.J., 1979. A flow diagram for teaching texture-by-feel analysis. *J. Agron. Educ.* 8, 54–55. <https://doi.org/10.2134/jae.1979.0054>.
- Thierfelder, C., Mhlanga, B., Nyagumbo, I., Kalala, K., Simutowe, E., Chiduwa, M., MacLaren, C., Silva, J.V., Ngoma, H., 2024. Two crops are better than one for nutritional and economic outcomes of Zambian smallholder farms, but require more labour. *Agric. Ecosyst. Environ.* 361, 108819. <https://doi.org/10.1016/j.agee.2023.108819>.
- Toker, P., Canci, H., Turhan, I., Isci, A., Scherzinger, M., Kordrostami, M., Yol, E., 2024. The advantages of intercropping to improve productivity in food and forage production—a review. *Plant Prod. Sci.* 27, 155–169. <https://doi.org/10.1080/1343943X.2024.2372878>.
- Veres, A., Wyckhuys, K.A., Kiss, J., Tóth, F., Burgio, G., Pons, X., Avilla, C., Vidal, S., Razinger, J., Bazok, R., 2020. An update of the Worldwide Integrated Assessment (WIA) on systemic pesticides. Part 4: alternatives in major cropping systems. *Environ. Sci. Pollut. Res.* 27, 29867–29899. <https://doi.org/10.1007/s11356-020-09279-x>.
- Wang, L., Yu, X., Gao, J., Ma, D., Guo, H., Hu, S., 2023. Patterns of influence of meteorological elements on maize grain weight and nutritional quality. *Agronomy* 13, 424. <https://doi.org/10.3390/agronomy13020424>.
- Wang, L., Garland, G.M., Ge, T., Guo, S., Kebede, E.A., He, C., Hijri, M., Plaza-Bonilla, D., Stringer, L.C., Davis, K.F., 2025a. Integrated strategies for enhancing agrifood productivity, lowering greenhouse gas emissions, and improving soil health. In: *The Innovation*.
- Wang, W., Li, M.-Y., Wang, Y., Li, J.-M., Zhang, W., Wen, Q.-H., Huang, S.-J., Chen, G.-R., Zhu, S.-G., Wang, J., 2025b. Legume intercropping improves soil organic carbon stability in drylands: a 7-year experimental validation. *Agric. Ecosyst. Environ.* 381, 109456.
- Witcombe, A.M., Tiemann, L.K., 2022. Potential contribution of groundnut residues to soil N and the influence of farmer management in western Uganda. *Front. Sustain. Food Syst.* 5, 691786. <https://doi.org/10.3389/fsufs.2021.691786>.
- Yang, M., Zhou, D., Hang, H., Chen, S., Liu, H., Su, J., Lv, H., Jia, H., Zhao, G., 2024. Effects of balancing exchangeable cations Ca, Mg, and K on the growth of tomato seedlings (*Solanum lycopersicum* L.) based on increased soil cation exchange capacity. *Agronomy* 14, 629. <https://doi.org/10.3390/agronomy14030629>.
- Yila, K.M., Lebbie, M.S., Conteh, A.R., Kamara, M.S., Kamara, L.I., Gboku, M.L., 2023. Cassava groundnut intercropping: a sustainable land management practice for increasing crop productivity and organic carbon stock on smallholder farms. *Agric. Sci.* 14, 73–87. <https://doi.org/10.4236/as.2023.141006>.
- Yu, H., Wang, F., Shao, M., Huang, L., Xie, Y., Xu, Y., Kong, L., 2021. Effects of rotations with legume on soil functional microbial communities involved in phosphorus

- transformation. *Front. Microbiol.* 12, 661100. <https://doi.org/10.3389/fmicb.2021.661100>.
- Zhang, S., Li, S., Meng, L., Liu, X., Zhang, Y., Zhao, S., Zhao, H., 2024a. Root exudation under maize/soybean intercropping system mediates the arbuscular mycorrhizal fungi diversity and improves the plant growth. *Front. Plant Sci.* 15, 1375194. <https://doi.org/10.3389/fpls.2024.1375194>.
- Zhang, W.-P., Surigaogee, S., Yang, H., Yu, R.-P., Wu, J.-P., Xing, Y., Chen, Y., Li, L., 2024b. Diversified cropping systems with complementary root growth strategies improve crop adaptation to and remediation of hostile soils. *Plant Soil* 502, 7–30. <https://doi.org/10.1007/s11104-023-06464-y>.