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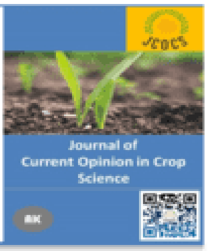

RESEARCH ARTICLE

Phenological performance and yield response of maize under different legume–cereal intercropping systems in Morogoro region

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ABSTRACT

This study evaluated the agronomic performance and land-use efficiency of maize–bean intercropping systems in Morogoro District, Tanzania. Three planting patterns were assessed: sole cropping (maize and beans), mixed intercropping, and row intercropping. Data were collected on plant population, flowering days, plant height, grain rows per cob, cob length and girth, pods per plant, seed count, and land equivalent ratio (LER). Statistical analysis using ANOVA ($p < 0.05$) revealed significant treatment differences. Mixed intercropping exhibited the highest maize cob length (23.0 cm), number of grain cobs (449.3), and plant height (2.967 m), while also outperforming in bean yield attributes such as pod number (20 pods/plant) and seed count (100 seeds/plant). There was a significant increase in bean plant population at thinning in mixed intercropping (78 plants) compared to sole bean cropping (32 plants). However, no significant difference was observed in germination rate across treatments ($p > 0.05$). Land Equivalent Ratio (LER) analysis showed that mixed intercropping achieved an LER of 1.32, while row intercropping recorded 1.15, indicating a 32% and 15% higher land productivity, respectively, compared to sole cropping systems. These results confirm the efficiency of cereal–legume intercrops in improving yield components and optimizing land use. Overall, the findings underscore the agronomic and ecological advantages of mixed intercropping for sustainable food production and land-use intensification in smallholder farming systems.

Keywords: Maize-bean intercropping; land equivalent ratio; yield performance; crop diversity; sustainable food production

INTRODUCTION

Intercropping systems, particularly legume cereal combinations such as maize (*Zea mays L.*) and common beans (*Phaseolus vulgaris L.*), have gained considerable attention as sustainable agricultural strategies for improving resource use efficiency, crop productivity, and soil health, especially in sub-Saharan Africa (Mucheru-Muna et al., 2020; Midega et al., 2015). In the Morogoro Region of Tanzania, where smallholder farmers face declining soil fertility, erratic rainfall, and limited access to inputs, intercropping offers a practical approach to enhancing food security while conserving natural resources (Kimaro et al., 2019). Phenological performance measured through parameters such as days to emergence, flowering, and physiological maturity is a critical indicator of crop adaptability and productivity in varied agro-ecological zones (Makungu et al., 2021). Field evaluations have shown that appropriate intercropping patterns, such as alternate or paired rows, can minimize interspecific competition for light, water, and nutrients while promoting complementary resource utilization between legumes and cereals (Assefa et al., 2017; Dapaah et al., 2018). Moreover, legume integration improves nitrogen availability through biological nitrogen fixation, benefiting the associated cereal crops and contributing to increased grain yield and system productivity (Snapp et al., 2019; Vanlauwe et al., 2021). However, intercropping systems' success in terms of phenological synchrony and yield output is highly dependent on spatial arrangement, planting time, and varietal compatibility.

Recent research from various agro-ecological regions has consistently demonstrated the agronomic and ecological benefits of integrating grain legumes through intercropping or rotation with cereals, particularly in enhancing cereal yields. These benefits are primarily attributed to legumes' improved nitrogen availability resulting from biological nitrogen fixation (BNF) (Vanlauwe et al., 2019; Snapp et al., 2019). Developing cropping systems that optimize yield per unit area while reducing dependence on synthetic nitrogen fertilizers remains a key goal for sustainable agriculture in sub-Saharan Africa (Makungu et al., 2021; Mucheru-Muna et al., 2020). Intercropping legumes with cereals and incorporating leguminous biomass offers a viable strategy for improving soil fertility and energy-efficient crop production (Kariaga et al., 2016; Abera et al., 2023).

Studies have shown that maize–legume intercrops often remove fewer nutrients from the soil than sole maize cropping, thereby contributing to better soil nutrient balance (Chimonyo et al., 2016). However, nutrient interactions within intercropping systems depend on nitrogen availability. When nitrogen fertilizer is applied, intercropped legumes may shift their nitrogen source from atmospheric fixation to soil nitrate, increasing competition with cereals like maize (Pypers et al., 2015). Conversely, in low-input systems where fertilizer is not applied, legumes predominantly meet their nitrogen demand through BNF, minimizing interspecific competition with maize (Vanlauwe et al., 2021). Optimizing maize–legume intercropping enhances yield stability and labor efficiency and reduces smallholder farmers' risk of total crop failure, contributing to long-term soil health and sustainability (Kimaro et al., 2019; Snapp et al., 2019). Therefore, evaluating various intercropping patterns under field conditions is essential to identify optimal combinations that enhance crop development stages and maximize grain yield under local agro-ecological constraints.

MATERIALS AND METHODS

Description of the Experimental Site

The field experiment evaluating cereal–legume intercropping patterns on crop phenology and grain yield was conducted at the Crop Museum of Sokoine University of Agriculture (SUA), located in Morogoro Region, eastern Tanzania. The site lies approximately 200 meters northwest of the Department of Crop Science and Horticulture. Geographically, the area is situated at an altitude of 525 meters above sea level, with coordinates at latitude 6°52′S and longitude 37°35′E. The region experiences a semi-humid tropical climate characterized by a bimodal rainfall pattern, with the long rainy season occurring from March to May and the short rains from October to December. The mean annual rainfall ranges between 600 mm and 1000 mm, while the average annual temperature fluctuates between 20°C and 30°C, supporting a wide range of rainfed agricultural activities (Kimaro et al., 2019). The soil at the experimental site is predominantly sandy loam in texture, classified under the Oxisol soil order, locally referred to as Ferralsols. These soils are typically well-drained but inherently low in fertility due to high weathering and leaching, with moderately acidic pH values averaging around 5.16 (Msanya et al., 2020). Despite these limitations, the soils are suitable for maize–legume intercropping when managed under proper nutrient supplementation and organic matter input. Prior to trial establishment, a composite soil sample was collected at a depth of 0–20 cm to assess baseline soil properties and guide fertilizer application. The site had been under regular agricultural use but was left fallow for a season before the experiment, ensuring minimal residual crop effects.

Experimental Plots

The experimental field was initially prepared using a tractor for primary tillage operations to ensure proper land leveling and soil pulverization. Secondary tillage was conducted manually using hand hoes and rakes to create a fine tilth suitable for planting. Sowing was carried out manually by placing one seed per planting hole at a depth of approximately 2.5 to 5 cm. Maize (Zea mays L.) was planted at an inter- and intra-row spacing of 75 cm × 30 cm, while common beans (*Phaseolus vulgaris* L.) were planted at 40 cm × 20 cm. For the row intercropping pattern, bean rows were interplanted between maize rows, maintaining the recommended bean spacing. In contrast, for the mixed intercropping pattern, beans were sown randomly between maize plants without adhering to a fixed planting geometry. Di-Ammonium Phosphate (DAP) fertilizer was applied at planting using the spot application method to provide essential phosphorus for early crop development. Post-planting management practices included manual irrigation using watering cans during dry spells, and weed control through hand hoeing and manual weeding. Pest control measures were undertaken to manage common pests affecting the crops.

Experimental Design and Treatment Application

The experiment was established using a Randomized Complete Block Design (RCBD) to minimize the effects of soil heterogeneity across the field. A total of four treatments were tested, each replicated three times, resulting in twelve experimental units. The treatments included: T1 – sole maize (control); T2 – maize intercropped with beans in a mixed intercropping; T3 – sole beans (control); and T4 – maize intercropped with beans in a row intercropping pattern. Each block (replication) contained all four treatments, and randomization was conducted according to the procedures outlined by Gomez and Gomez (1984) to ensure an unbiased distribution of treatments. This design was selected specifically because of the non-uniform soil characteristics of the experimental site, and blocking was employed to control for environmental variation and ensure more reliable comparison among treatments.

Experimental Layout and Area Determination

The experimental layout was designed to accommodate both sole and intercropped treatments with precise spacing for accurate yield and phenological assessments. For maize subplots, a spacing of 75 cm × 40 cm was used, comprising four rows per plot with seven plants per row. In the sole bean subplots, spacing was maintained at 40 cm × 20 cm, with five bean rows per plot and seven plants per row. Each subplot had a uniform width of 3 meters, with 1 meter allocated between individual plots and also between replications to facilitate movement and minimize treatment interference. Additionally, a 15 cm margin was maintained along each side of the plots during planting to reduce edge effects, and a buffer zone of 0.5 meters was established around the experimental field. The total layout dimensions were calculated by combining the area occupied by plots and the spacing between them. Specifically, the total width of the experimental area including three plots per replication and two 1-meter pathways was (3 m × 3) + 2 m = 11 meters, while the total length including four plots and three 1-meter pathways was (3 m × 4) + 3 m = 15 meters. Thus, the total area occupied by the experimental field was 11 m × 15 m = 165 m^2.

Data Collection

Parameters Collected for Both Maize and Beans

Number of Plants at Thinning and Harvesting

The number of plants present at thinning and at harvest was determined by direct counting. After seedling emergence, the number of established plants was recorded during thinning. At harvest, the number of surviving and harvestable plants was again counted. This data was collected separately for both maize and beans to evaluate plant survival and establishment rates.

Seedling Emergence Percentage (%)

Seedling emergence was assessed seven days after sowing (DAS) by counting the number of emerged seedlings relative to the total number of seeds sown. Emergence percentage was calculated using the formulaSeedling Emergence (%) = (Number of seeds germinated / Total seeds sown) × 100.
This measurement was recorded for both maize and bean plots.

Days to 50% Flowering

This parameter was defined as the number of days from sowing to the point when 50% of the plants in a given plot had reached flowering. Observations were made daily, and the proportion of flowering plants was compared against the total plant population per plot. The day when half the plants exhibited flowering characteristics was recorded as the flowering date for both maize and beans.

Plant Height

Plant height was measured for both crops at the vegetative and reproductive stages. For maize, a measuring tape was used due to the relatively tall stature of the crop, and height was recorded in meters from the soil surface to the tip of the tallest leaf or tassel. For beans, a metric ruler graduated in centimeters was used due to the crop's shorter stature. Measurements were taken from the base of the plant at soil level to the highest point of the plant canopy.

Data Collected on Beans

Number of Bean Plants/m^2

The plant population density (plants/m^2) was determined across all cropping patterns, including mixed intercropping, row intercropping, and sole bean plots. This was done by counting the number of established bean plants within a 1 m^2 area in each subplot. The counts were taken from three representative subplots per cropping system, and the mean number of plants per square meter was calculated for each treatment.

Number of Nodes per Plant

The number of nodes per plant was assessed by selecting 20 representative bean plants from each subplot. The nodes were counted manually, and the average number of nodes per plant was recorded for each plot. As only a single bean variety was used across all treatments, uniformity in node development was expected among the plots.

Number of Pods per Plant

To assess pod production, 20 plants per plot were randomly selected, and the number of pods per plant was counted. The average number of pods per plant was then computed for each subplot to evaluate reproductive performance under different cropping systems.

Pod Length

Pod length was measured using a standard ruler. A total of 20 pods from 10 bean plants were randomly selected per subplot as a representative sample. Each pod was measured from base to tip, and the mean pod length per plot was calculated. Since a uniform variety was planted across all treatments, pod size was assumed to be consistent.

Number of Seeds per Pod

The number of seeds per pod was determined a few days before harvesting by manually counting the seeds in 20 pods sampled from 10 different bean plants per subplot. The average number of seeds per pod was then computed to evaluate seed development and pod filling across different cropping treatments.

Data Collected on Maize

Cob Height (cm)

The height of maize cobs (ears) from the ground level was measured using a metric ruler. A total of 20 maize plants were randomly selected from each maize subplot, and the distance from the base of the plant to the attachment point of the cob was recorded. The average cob height was then calculated for each subplot.

Cob Girth (cm)

Cob girth was measured at three points the lower, middle, and upper sections of the cob using a flexible measuring tape or ruler. Measurements were taken from 20 cobs per subplot, and the average girth from the three sections was computed for each cob. These values were then averaged across the 20 samples to determine the mean cob girth for each maize subplot.

Number of Grain Rows per Cob

This parameter was determined by counting the number of grain rows on 10 randomly selected maize cobs per subplot. The average number of grain rows per cob was then computed to assess grain arrangement and potential yield performance.

Number of Kernels per Row

The number of kernels per row was also assessed manually by counting the grains on a single row of the same 10 sampled cobs. The average kernel count per row was recorded for each subplot.

Total Number of Grains per Cob

The total number of grains per cob was estimated by multiplying the average number of grain rows per cob by the average number of kernels per row (based on the 10 representative cobs per subplot). This provided an estimate of total grain number per cob, reflecting yield potential under each cropping treatment.

Land Equivalent Ratio (LER)

The Land Equivalent Ratio (LER) is a comparative index used to assess the productivity of intercropping relative to sole cropping. It is defined as the amount of land required under sole cropping to achieve the same yield as obtained from an intercropping system (Waddington et al., 1989). Thus, LER serves as an indicator of the efficiency with which intercropping systems utilize environmental resources compared to monocropping systems. LER can be employed to evaluate land-use efficiency by comparing the yields from pure stands with those from component crops in a mixed cropping system (Dariush et al., 2006). According to Muoneke et al. (2007), intercropping systems can yield productivity advantages ranging from 2% to 63%, as demonstrated by LER values ranging between 1.02 and 1.63. These values highlight the superior land-use efficiency of intercropping, where crops grown together outperform those planted separately. LER calculated using the formula proposed by Lithourgidis et al. (2011).

Data Analysis

Following the completion of data collection, yield component data were initially assessed for normality and homogeneity of variance. Data were subjected to analysis of variance (ANOVA) using the GENSTAT statistical software package (MSU, 1993). Statistical significance was evaluated at the 5% probability level ($P < 0.05$). The analyzed results were presented in the subsequent tables, as generated through the GENSTAT statistical software.

RESULTS

Maize Results

Number of plants at thinning

Analysis of variance revealed no statistically significant difference ($p > 0.05$) in the number of maize plants at thinning among the three cropping patterns. The mixed intercropping, row intercropping, and sole maize (control) treatments maintained comparable plant populations at this stage (Table 1).

Number of plants at harvest

Similarly, the number of plants at harvest did not differ significantly among treatments ($p > 0.05$). Both the sole maize and row intercropping treatments retained 25 plants, while the mixed intercropping treatment retained 27 plants, indicating uniform plant survival across all cropping systems. Furthermore, there were no significant differences ($p > 0.05$) in seedling emergence percentages among the treatments.

Days to 50% flowering

There were no significant differences ($p > 0.05$) in the number of days to 50% flowering across treatments. The mixed intercropping and sole maize treatments reached 50% flowering at 24 days, while the row intercropping pattern did so at 23 days, showing negligible variation in phenological development.

Number of grain rows per cobThe number of grain rows per cob did not show a statistically significant difference ($p > 0.05$) among treatments. All plots exhibited approximately equal numbers of rows per cob, indicating that cropping pattern did not influence this trait.

Grain rows per cob

A statistically significant difference ($p < 0.05$) was observed in the number of grain rows per cob among treatments. The sole maize treatment produced the highest number of grain rows (36), followed by the mixed intercropping treatment (31), while the row intercropping treatment had the lowest value.

Number of grain cobs

The number of grain cobs per plot differed significantly among treatments ($p < 0.05$). The sole maize treatment recorded the highest cob count (559), compared to the mixed intercropping (449 cobs) and row intercropping (445 cobs), indicating a yield advantage under monoculture.

Maize cob length & cob Girth

Cob length was significantly affected by cropping pattern ($p < 0.05$). The sole maize treatment produced longer cobs (23.0 cm), compared to the row intercropping (21.33 cm) and mixed intercropping (20.33 cm) treatments. There was no significant difference ($p > 0.05$) in cob girth (cm) among the treatments, as confirmed by the Tukey–Kramer Multiple Comparison test, indicating similar cob girth across all cropping patterns.

Table 1. Mean Values of Agronomic Parameters of Maize under Different Maize–Bean Intercropping Patterns

Treatment	Plants at Thinning	Plants at Harvest	Seedling Emergence	Plant Height	Days 50% Flowering	Grain Row/ Cob	Grain Rows /Cob	Grain Cobs	Cob Length	Cob Girth
Mixed Intercropping	27.00^{b}	26.67^{b}	96.40^{b}	2.967^{b}	24.00^{b}	14.67^{b}	30.67^{b}	449.3^{b}	20.33^{b}	16.07^{bc}
Sole Beans	0.00^{a}	0.00^{a}	0.00^{a}	0.000^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}
Row Intercropping	27.33^{b}	25.33^{b}	97.60^{b}	2.967^{b}	22.67^{b}	15.33^{b}	29.00^{b}	445.3^{b}	21.33^{bc}	15.53^{b}
Sole Maize	27.00^{b}	25.00^{b}	96.40^{b}	2.967^{b}	24.00^{b}	15.67^{b}	35.67^{b}	559.0^{b}	23.00^{c}	16.30
Grand Mean	20.33	19.25	72.60	2.225	17.67	11.42	23.83	363.0	16.17	11.97
CV (%)	1.9	1.3	1.9	1.1	5.9	3.3	2.4	0.9	7.0	2.5
LSD	1.526	1.793	5.493	0.1913	3.052	1.793	2.664	81.1	2.469	1.088
P-value (5%)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

The values with the same letter are non-significant at $p \leq 0.05$ (Tukey–Kramer Multiple Comparison test), and the values with different letters are significantly different at $p \leq 0.05$ (Tukey–Kramer Multiple Comparison test)

Bean results

Number of plants at thinning

A statistically significant difference ($p < 0.05$) was observed among treatments in the number of bean plants at thinning. The mixed intercropping pattern recorded the highest plant count (78 plants), followed by the row intercropping pattern (38 plants), whereas the sole bean treatment (control) recorded the lowest number of plants (32 plants) (Table 2).

Number of plants at harvest

The number of bean plants at harvest differed significantly among the treatments ($p < 0.05$). The mixed intercropping system resulted in the highest plant count at harvest (74 plants), followed by the row intercropping pattern (34 plants), and while the sole bean treatment had the fewest plants remaining at harvest (28 plants).

Germination percentage (%)

There was no statistically significant difference in germination percentage among treatments ($p > 0.05$). Germination rates were similar across plots, with values of 92.47% for the mixed intercropping pattern, 92.37% for the sole bean treatment, and 90.47% for the row intercropping pattern.

Plant density (Plants per m²)

A significant difference ($p < 0.05$) was found in plant density among the treatments. The mixed intercropping pattern exhibited the highest density (24 plants/m^2), followed by the row intercropping pattern (14 plants/m^2), and whereas the sole bean treatment recorded the lowest density (12 plants/m^2).

Days to 50% flowering

No significant difference ($p > 0.05$) was observed in the number of days to 50% flowering among treatments, according to the Tukey–Kramer Multiple Comparison test. Flowering time was consistent across all patterns, including the sole bean treatment, row intercropping, and mixed intercropping.

Plant height

There was a statistically significant difference ($p < 0.05$) in plant height among treatments. Plants in the mixed intercropping pattern attained the greatest average height (27.6 cm), while those in the sole bean treatment were significantly shorter (22.9 cm).

Number of pods per plant

The number of pods per plant varied significantly among treatments ($p < 0.05$). The mixed intercropping pattern recorded the highest pod count (20 pods/plant), while both the row intercropping pattern and sole bean treatment produced fewer pods (18 pods/plant).

Number of seeds per Plant

A significant difference ($p < 0.05$) was also observed in the number of seeds per plant. The mixed intercropping pattern resulted in the highest seed count (100 seeds/plant), followed by the row intercropping and sole bean patterns, which both recorded lower seed numbers (92 seeds/plant).

Table 2. Mean Values of Agronomic Parameters of Bean under Different Maize–Bean Intercropping Patterns

Treatment	No. of plants at harvest	No. of plants at thin	Plant height (m)	Plants (m^2)	Days to 50% flowering	Germination (%)	Pod length (cm)	Pod/plant	Yield
Mixed intercropping	74^{d}	78^{d}	27.63^{c}	23.67^{d}	26.00^{b}	92.47^{b}	11.933^{b}	20.00^{c}	100.00^{c}
Sole beans	28^{b}	32^{b}	22.90^{b}	9.67^{b}	27.33^{b}	92.37^{b}	12.033^{b}	18.33^{b}	91.67^{b}
Row intercropping	34^{c}	38^{c}	24.10^{bc}	14.00^{c}	26.33^{b}	90.47^{b}	12.000^{b}	18.33^{b}	91.67^{b}
Sole maize	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}
Grand mean	34.00	37.00	18.66	11.83	19.92	68.8	8.992	14.17	70.83
CV (%)	4.8	2.4	4.1	4.9	2.6	2.4	0.2	1.332	6.660
LSD	6.203	4.380	4.041	1.762	2.469	9.89	0.1451	2.0	2.0
P value (5%)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

The values with the same letter are non-significant at $p \leq 0.05$ (Tukey – Kramer Multiple Comparison test), and the values with different letters are significantly different at $p \leq 0.05$ (Tukey – Kramer Multiple Comparison test)

Land Equivalent Ratio (LER) Analysis

The Land Equivalent Ratio (LER) values showed considerable variation among the different cropping patterns, indicating differences in land use efficiency (Table 3). The highest LER was recorded under the mixed intercropping pattern (maize-legume with three bean lines between maize rows), with a value of 1.32, suggesting a 32% land use advantage compared to mono-cropping. This implies that the mixed intercropping system utilized the land more efficiently and provided a greater combined yield than would be expected from the same area under sole cropping. The row intercropping pattern (maize-legume with two bean lines between maize rows) had a moderate LER value of 1.15, indicating a 15% land use benefit over sole cropping. In contrast, the control treatment (sole cropping) exhibited a significantly lower LER value of 0.15, highlighting the inefficiency of mono-cropping in terms of land productivity compared to intercropping systems. Overall, LER values greater than 1 for both intercropping treatments confirm the yield advantage and improved resource utilization of intercropping systems over monocropping. The mixed intercropping system, in particular, demonstrated the highest productivity and land-use efficiency among the evaluated patterns.

Table 1. Land equivalent ratio for various maize-beans intercropping patterns

Sl. No	Planting pattern	LER
1	Control treatment	0.15
2	Maize-Legume three bean line between maize rows (mixed intercropping pattern)	1.32
3	Maize–Legume two line between maize rows (row intercropping pattern)	1.15

LER for mixed pattern > LER for row intercropping pattern and sole pattern; therefore, it was observed that the mixed pattern of intercropping performed better than the row intercropping pattern

DISCUSSION

Intercropping maize with beans significantly improved key growth parameters such as plant height, cob length, and cob number, ultimately enhancing grain yield. In our study, although maize in both mixed and row intercropping patterns reached a similar plant height (2.967 m), intercropping, especially with the mixed format, led to longer cob length and more grain cobs than row intercropping and sole maize. These findings align with reports by Mebrahtu et al. (2021), who observed that maize intercropped with soybean or cowpea significantly outperformed sole maize in plant height, grain yield, and yield-related traits ($p < 0.01$) Similarly, a study in Southeastern Tigray showed that maize intercropped with cowpea produced a cob length of 19.3 cm compared to 18.5 cm in maize–soybean systems, highlighting the benefit of multiple legume companions. These synergistic benefits are likely due to improved light use efficiency and nutrient availability (e.g., enhanced N and P availability) in intercropped plots, consistent with broader findings on resource complementarity in cereal–legume systems.

Bean components also responded strongly to intercropping systems. Though germination and flowering time remained unaffected across treatments, variables such as plant height, pod number, and seed number per plant were significantly increased in the mixed intercropping pattern. Specifically, beans in mixed intercropping exhibited greater plant height (27.6 vs. 22.9 cm), more pods per plant (20 vs. 18), and more seeds per plant (100 vs. 92), supporting similar findings from Amanullah et al. (2020), who reported improved vegetative and reproductive growth when beans were intercropped under efficient resource use regimes.

Land Equivalent Ratio (LER) analysis clearly demonstrates the efficiency of intercropping systems in utilizing land resources. In this study, the mixed intercropping pattern yielded an LER of 1.32. In contrast, the row intercropping pattern recorded an LER of 1.15, exceeding the standard threshold of 1.0, indicating superior productivity compared to mono-cropping. These results translate to a 32% and 15% advantage in land-use efficiency, respectively. Similar findings have been reported in recent studies, where LER values ranged between 1.30 and 1.38 for maize intercropped with legumes like cowpea or soybean (Li et al., 2021; Garba et al., 2022; Kamara et al., 2020). The observed advantages are often attributed to complementary interactions such as improved nitrogen availability from legume fixation and more effective spatial resource partitioning (Tadele & Afework, 2018; Agegnehu et al., 2016).

The consistently higher yield components observed in maize and beans under the mixed intercropping pattern, coupled with enhanced LER values, affirm this system's agronomic and ecological benefits. Intercropping enhances overall system productivity while promoting efficient resource utilization and resilience in smallholder farming systems, making it a viable strategy for sustainable intensification (Meena et al., 2020; Chimonyo et al., 2020; Lithourgidis et al., 2019).

CONCLUSION

The findings of this study clearly demonstrate that maize–bean intercropping, particularly in a mixed intercropping pattern, significantly enhances agronomic performance and land-use efficiency compared to monocropping systems. Mixed intercropping consistently outperformed other treatments in critical maize yield components such as number of cobs, cob length, grain rows per cob, and overall grain yield. Similarly, common bean performance was markedly improved under the mixed pattern, with higher plant population at harvest, pod count, and seed yield per plant, highlighting the beneficial interaction between legumes and cereals in resource sharing. Significantly, the Land Equivalent Ratio (LER) values exceeded unity for both intercropping systems, with the mixed pattern achieving an LER of 1.32, indicating a 32% land productivity advantage over monoculture. It confirms the agronomic and ecological complementarity of the maize–bean system and underscores its value in addressing land scarcity and improving food security in smallholder farming contexts. These results align with global research trends emphasizing intercropping as a low-cost, climate-resilient strategy that supports sustainable intensification through better nutrient use, improved soil fertility, and efficient spatial resource management. Overall, this study provides strong empirical support for adopting maize–bean intercropping, particularly the mixed pattern, as a viable option for smallholder farmers aiming to maximize yield, improve soil health, and optimize land use in resource-constrained environments.

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AUTHORS CONTRIBUTIONS

All authors contributed substantially to this study. Patrick Cleophace Mpombeye was responsible for conceptualization, methodology, data collection, formal analysis, drafting the original manuscript, and coordinating the overall write-up. Akwilin Joseph Peter Tarimo; contributed to supervision, guidance on study design, interpretation of findings, and critical review of the manuscript. Andrea Malima Kigeso provided field supervision, technical expertise on production, validation of results, and assisted with reviewing and editing the manuscript. All authors have read and approved the final version of the manuscript for submission.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICAL APPROVAL

This research was conducted in accordance with institutional, national, and international ethical standards. All experimental procedures involving field trials were reviewed and approved by the Department of Crop Science and Horticulture, Sokoine University of Agriculture. The study involved no human or animal subjects. Before fieldwork, informed verbal consent was obtained from all participating farmers and farm managers for access to the fields and for conducting intercrop trials. The study did not involve the collection of any personal data or sensitive information. All data collected was anonymized and used solely for academic and scientific purposes.

FUNDING

No funds were obtained for this study.

AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

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