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RECEIVED 13 January 2026

REVISED 03 March 2026

ACCEPTED 09 March 2026

PUBLISHED 27 March 2026

CITATION

Ndibalema LR, Alavaisha E, Manoko MLK
and Joseph CO (2026) Short-term soil,
growth and yield responses to Lablab
intercropped with maize and sorghum in
dryland agroecological zone of Tanzania.
Front. Agron. 8:1786627.
doi: 10.3389/fagro.2026.1786627

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Short-term soil, growth and yield responses to Lablab intercropped with maize and sorghum in dryland agroecological zone of Tanzania

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Smallholder farmers in semi-arid regions of Tanzania face multiple challenges, including erratic rainfall, prolonged droughts, and soil degradation, which threaten both crop yields and food security. Cereal-legume intercropping has been proposed as a sustainable strategy to enhance soil health, nutrient availability, and productivity under these conditions. This study evaluated the potential of intercropping maize (*Zea mays*) and sorghum (*Sorghum bicolor*) with three legumes Lablab purpureus, cowpea (*Vigna unguiculata*), and common bean (*Phaseolus vulgaris*) at TARI Makutupora, Dodoma, Tanzania. A randomized complete block design with three replications was used to assess effects on soil physical and chemical properties, microbial abundance, and crop performance. Intercropping systems significantly improved soil nitrogen (up to 0.17%), microbial populations (up to 4.8×10^5 CFU g⁻¹), and soil moisture (up to 14%) compared with sole cereal crops. Path analysis indicated that soil moisture ($\beta = 0.419$) and nitrogen ($\beta = 0.345$) were the most influential factors for productivity. Among legumes, Lablab-based intercrops consistently enhanced soil fertility and crop yield, achieving land equivalent ratios above 1.5 and outperforming other legume intercrops. These findings demonstrate that cereal-legume intercropping, particularly with Lablab, can revitalize semi-arid soils, improve water and nutrient use efficiency, and enhance food security. This approach provides a scalable, climate-resilient strategy for sustainable intensification in Tanzania's drylands.

KEYWORDS

dryland agriculture, intercropping, land equivalent ratio, smallholder farming, soil fertility, Tanzania

1 Introduction

Agriculture is central to food security, livelihoods, and economic growth globally. In Sub-Saharan Africa, it engages over 60% of the population and contributes 20–30% of GDP, with Tanzania's agriculture employing more than 65% of the population and accounting for 26% of the national GDP (World Bank, 2021; United Republic of Tanzania (URT), 2020). Despite its importance, smallholder farmers in semi-arid regions of Tanzania face multiple constraints, including erratic rainfall, prolonged droughts, soil degradation, and nutrient depletion, which collectively reduce crop productivity and threaten food security (Mkonda and He, 2018). Addressing these challenges requires innovative, resource-efficient farming systems that restore soil health while increasing yield resilience.

Cereal-legume intercropping is a promising agroecological strategy for semi-arid regions, as legumes contribute to biological nitrogen fixation, improve soil structure, conserve moisture, and diversify farmers' sources of food and income (Brooker et al., 2015). Among commonly grown legumes in Tanzania, cowpea and common bean are widely consumed but often fail under prolonged dry conditions due to limited drought tolerance. In contrast, *Lablab purpureus*, a drought-tolerant and multifunctional legume native to Africa, remains underutilized, occupying less than 2% of the country's legume production area (Muthamia et al., 2020). *Lablab* is well-suited for degraded soils, capable of fixing 20–30 kg N per tonne of biomass annually, producing 1.5–2.5 t ha⁻¹ of dry matter, and improving soil moisture retention, making it particularly valuable for climate-resilient farming systems (Maass et al., 2010; Muthamia et al., 2020).

While previous studies have documented the benefits of *lablab* in intercropping systems, few field-based investigations have quantified its effects on soil fertility, microbial abundance, and productivity in semi-arid Tanzanian conditions. Moreover, comparative evaluations with other legumes such as cowpea and common bean remain limited. Understanding these dynamics is crucial for informing sustainable intensification strategies that can enhance soil health, stabilize yields, and improve food security under climate stress.

This study aimed to evaluate the potential of cereal-legume intercropping for revitalizing semi-arid soils and improving crop yields in Tanzania, with a particular focus on *Lablab purpureus*. Specifically, we assessed the effects of intercropping maize and sorghum with *Lablab*, cowpea, and common bean on soil chemical and physical properties, microbial abundance, and crop productivity, using land equivalent ratio as a measure of intercropping efficiency. This research provides evidence-based insights for smallholder farmers and policymakers seeking climate-resilient and sustainable intensification strategies in semi-arid agroecosystems.

2 Materials and methods

2.1 Study area

The study was conducted at the Tanzania Agricultural Research Institute (TARI) Makutupora in Dodoma, a semi-arid region characterized by low and erratic rainfall (400–800 mm per year) and

sandy-loam soils with low organic matter (Figure 1). The area experiences mean annual temperatures of 22–28 °C, making it representative of semi-arid farming conditions in central Tanzania (United Republic of Tanzania (URT), 2020).

2.2 Experimental design

A field experiment was conducted during the 2024/2025 cropping season to evaluate cereal-legume intercropping in semi-arid Tanzania. The study used a randomized complete block design (RCBD) with three replications. Two cereals maize (*Zea mays*) and sorghum (*Sorghum bicolor*) were intercropped with three legumes *Lablab* (*Lablab purpureus*), cowpea (*Vigna unguiculata*), and common bean (*Phaseolus vulgaris*) in a 1:1 row arrangement. In addition, sole crops of each cereal and legume were included as controls. In total, the experiment comprised 11 treatments, covering all cereal-legume intercrop combinations and the sole crops. Each plot measured 5 m × 4 m, with 0.5 m buffer zones between plots to minimize edge effects. The RCBD layout ensured that each treatment appeared once in each block, allowing for reliable comparison of crop performance under intercropping and sole cropping systems.

2.3 Crop establishment and management

Land was ploughed and harrowed prior to planting. Crops were sown at recommended plant densities: Maize: 53,000 plants ha⁻¹ (75 cm × 25 cm). Sorghum: 100,000 plants ha⁻¹ (75 cm × 20 cm). *Lablab*: 25,000 plants ha⁻¹ (50 cm × 50 cm). Cowpea: 30,000 plants ha⁻¹ (50 cm × 20 cm). Common bean: 40,000 plants ha⁻¹ (50 cm × 20 cm). In intercropped treatments, cereals and legumes were planted in alternating rows (1:1 configuration). Planting occurred at the onset of seasonal rains in November 2024.

2.4 Soil sampling and laboratory analysis

Soil samples were collected before planting and immediately after harvest at three depths (0–10 cm, 10–20 cm, and 20–30 cm). Composite samples were prepared from multiple cores per plot. The following parameters were analyzed; Soil pH: 1:2.5 soil-water suspension (Thomas, 1996). Soil organic carbon (SOC), Walkley-Black method (Walkley and Black, 1934). Total nitrogen (N): Kjeldahl digestion method (Bremner, 1960). Available phosphorus (P), Olsen method (Olsen et al., 1954). Exchangeable potassium (K): Flame photometry following ammonium acetate extraction (Chapman, 1965). Cation exchange capacity (CEC), Ammonium acetate method (Chapman, 1965). Soil moisture: Gravimetric method. Soil temperature: Field probe measurement at 10 cm depth.

2.4.1 Microbial abundance assessment

Microbial abundance was quantified using colony-forming unit (CFU) enumeration via serial dilution and plate count techniques (Alef and Nannipieri, 1995). This method estimates viable culturable microorganisms but does not capture non-culturable taxa or full microbial diversity. Therefore, results represent relative biological activity rather than complete microbial community structure.

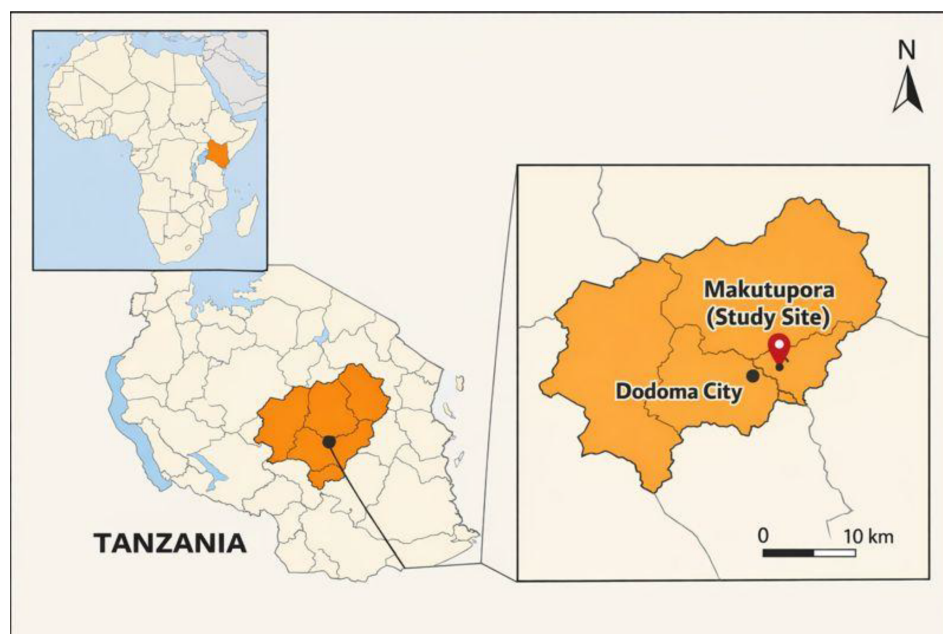


FIGURE 1

Location of the experimental site in Makutupora Ward, Dodoma Region, Tanzania (red dot). Dodoma City is shown for reference.

2.5 Crop growth and yield measurements

Phenological stages (days to 50% flowering and physiological maturity) were recorded. Growth measurements included plant height, leaf area index (LAI), and aboveground biomass.

Grain yield was determined from the central 3 m × 3 m area of each plot and adjusted to 12% moisture content.

Intercropping efficiency was evaluated using the Land Equivalent Ratio (LER), calculated as Equation 1:

$$LER = \frac{YA_1}{YA_2} + \frac{YB_1}{YB_2} \quad (1)$$

Where: YA_1 and YB_1 represent the yields of crops A and B under intercropping, respectively, while YA_2 and YB_2 represent the corresponding yields under monocropping (Willey, 1979).

2.6 Farmer perception assessment

Farmer perceptions were assessed using a structured questionnaire administered to 376 farmers who participated in field demonstrations during the 2024/2025 cropping season. Farmers were selected purposively from surrounding communities practicing cereal-legume farming. The survey captured perceptions on yield performance, soil moisture retention, labor requirements, and system preference using Likert-scale and open-ended questions. Responses were summarized using descriptive statistics in R software. Participation was voluntary and conducted in accordance with ethical research standards.

2.7 Statistical analysis

Data were analyzed using R version 4.2.1.

ANOVA was conducted under the RCBD framework, with cropping system as a fixed effect and block as a random effect. Assumptions of normality and homogeneity of variance were evaluated using Shapiro-Wilk and Levene's tests.

Treatment means were separated using Tukey's HSD at $p \leq 0.05$. Pearson correlation analysis was performed to identify relationships among soil variables and productivity indicators.

2.7.1 Structural equation modeling

A parsimonious structural equation model was specified *a priori* to evaluate direct and indirect effects of key soil variables on combined yield and LER. Given the sample size ($n = 33$ experimental units), the model was restricted to a limited number of biologically meaningful predictors to maintain an acceptable observation-to-parameter ratio. Model fit was evaluated using Chi-square (χ^2), RMSEA, CFI, and SRMR indices. Standardized path coefficients were used for interpretation.

3 Results and discussion

3.1 Soil characteristics and baseline fertility

Soil analysis at the Makutupora experimental site indicated sandy loam texture, low organic matter (1.2–1.5%), slightly acidic pH (5.8–6.3), and moderate nutrient levels (N: 0.09–0.12%, P: 10–15 mg/kg, K: 150–170 mg/kg). Electrical conductivity was low (<0.5 dS/m), suggesting minimal salinity stress. These semi-arid Dodoma soils typically limit cereal productivity, especially for nutrient-demanding crops. The low fertility underscores the potential benefits of integrating legumes such as lablab, which fix

atmospheric nitrogen and enhance soil nutrient status over time. These findings are consistent with previous reports from semi-arid Tanzania, where legume intercropping improved soil nitrogen and organic carbon (Ndibalema et al., 2026a; 2026b; Mowo et al., 2021).

3.2 Germination, establishment, and phenology

All cereal-legume combinations successfully germinated under the prevailing semi-arid conditions. Lablab initially showed slower emergence (52% at 0 cm burial depth) due to its hard seed coat but reached 85-90% emergence by the second week. Cowpea and common bean germinated faster (70-95%) and flowered 7–10 days earlier than lablab. Intercropped cereals matured within 90–110 days (maize) and 100–120 days (sorghum), whereas lablab matured in up to 140 days. The extended growth of lablab provides prolonged soil cover and nitrogen fixation, benefiting subsequent crops, aligning with observations from East African drylands (Ndiritu et al., 2022; Mutema et al., 2023).

3.3 Soil moisture and nutrient dynamics

Lablab-based intercropping systems consistently enhanced soil moisture retention and nutrient dynamics compared to sole cereals and other legumes (Table 1). Maize + lablab and sorghum + lablab increased soil moisture by 13.8% and 13.2%, respectively, relative to sole maize (11.4%) and sorghum (11.1%), demonstrating lablab’s water-conserving effect through dense canopy cover and extensive root systems. The observed improvements likely reflect multiple interacting mechanisms: canopy cover reduces direct soil exposure, lowering evaporative losses under semi-arid conditions, while root exudates and residue inputs enhance soil aggregation and porosity, thereby improving infiltration and water-holding capacity (Bünemann et al., 2018; Whitbread et al., 2011). These processes align with ecological theories of facilitation and niche complementarity in cereal-legume systems.

Enhanced soil nitrogen availability in intercropped plots can be attributed to biological nitrogen fixation and reduced nutrient leaching due to improved ground cover. Total soil N was elevated in maize + lablab (0.17%) and sole lablab (0.20%), confirming lablab’s nitrogen-fixing capacity and its contribution to soil fertility (Maass et al., 2010; Whitbread et al., 2011). Microbial abundance peaked in sole lablab (5.0×10^5 CFU g⁻¹) and maize + lablab (4.7×10^5 CFU g⁻¹), highlighting legume residues and root exudates as stimulants for beneficial soil microbial communities (Bünemann et al., 2018; Zhou et al., 2023).

While C:N ratios and K index (soil erodibility) did not differ significantly ($p > 0.05$), lablab-based systems showed modest reductions in K, suggesting slight erosion mitigation through improved soil structure and cover. These improvements indicate that lablab intercropping can enhance both soil fertility and microclimatic conditions in semi-arid environments. However, given the study’s two-season duration, these responses likely represent short- to medium-term effects from residue inputs and rhizosphere activity rather than fully stabilized, long-term soil fertility shifts. Sustained multi-season trials are required to determine

TABLE 1 Effect of cereal-legume (maize/sorghum with Lablab, cowpea, and common bean) intercropping on soil properties, microbial abundance, and crop productivity in semi-arid Tanzania.

Cropping system	Moisture (%)	Temp (°C)	Total N (%)	CFU g ⁻¹ (x10 ⁵ , DW)	C: N Ratio	K Index	Combined yield (kg ha ⁻¹)	LER
Maize + Lablab	13.8 ± 0.3a	28.2 ± 0.3ab	0.18 ± 0.01a	4.7 ± 0.2a	11.2 ± 0.2a	0.26 ± 0.01a	1,220 ± 30	1.61
Maize + Cowpea	13.2 ± 0.2ab	28.5 ± 0.2ab	0.16 ± 0.01a	4.3 ± 0.2ab	11.5 ± 0.2a	0.28 ± 0.01a	1,175 ± 28	1.55
Maize + Common Bean	12.9 ± 0.3ab	28.6 ± 0.3a	0.15 ± 0.01a	4.0 ± 0.2ab	11.8 ± 0.2a	0.29 ± 0.01a	1,050 ± 25	1.42
Sole Maize	11.4 ± 0.2c	28.9 ± 0.3a	0.12 ± 0.01b	3.2 ± 0.2c	12.3 ± 0.3a	0.31 ± 0.01a	820 ± 20	1.00
Sorghum + Lablab	13.5 ± 0.2a	27.9 ± 0.3ab	0.17 ± 0.01a	4.6 ± 0.2a	11.1 ± 0.2a	0.25 ± 0.01a	1,190 ± 30	1.59
Sorghum + Cowpea	12.8 ± 0.3ab	28.1 ± 0.2ab	0.15 ± 0.01a	4.2 ± 0.2ab	11.6 ± 0.2a	0.27 ± 0.01a	1,145 ± 27	1.51
Sorghum + Common Bean	12.4 ± 0.3b	28.3 ± 0.3ab	0.14 ± 0.01a	3.9 ± 0.2ab	11.9 ± 0.3a	0.28 ± 0.01a	1,020 ± 25	1.38
Sole Sorghum	11.1 ± 0.2c	28.7 ± 0.3a	0.11 ± 0.01b	3.0 ± 0.2c	12.4 ± 0.3a	0.32 ± 0.01a	840 ± 21	1.00
Sole Lablab	14.2 ± 0.4a	25.5 ± 0.2b	0.20 ± 0.01a	5.0 ± 0.2a	10.8 ± 0.2a	0.24 ± 0.01a	190 ± 10	1.00
Sole Cowpea	13.7 ± 0.3a	27.6 ± 0.3b	0.18 ± 0.01a	4.5 ± 0.2a	11.0 ± 0.2a	0.26 ± 0.01a	580 ± 18	1.00
Sole Common Bean	13.5 ± 0.3ab	27.7 ± 0.3b	0.17 ± 0.01a	4.1 ± 0.2ab	11.4 ± 0.2a	0.27 ± 0.01a	430 ± 15	1.00

Values are means ± SE; different letters within a column indicate significant differences ($p < 0.05$).

whether these trends translate into persistent improvements in soil structure, nutrient cycling, and ecosystem function.

3.4 Microbial abundance and growth of cereal–legume intercrops

Intercropping significantly influenced both soil biological conditions and crop growth parameters. Increases in microbial abundance (culturable fraction) under lablab-based intercrops suggest enhanced soil biological activity, likely driven by greater root biomass and organic inputs. Legume residues provide labile carbon substrates that stimulate microbial proliferation, particularly among culturable heterotrophic populations (Bünemann et al., 2018; Zhou et al., 2023). However, it is important to interpret these findings cautiously, as colony-forming unit (CFU) enumeration captures only the culturable fraction of the microbial community and does not reflect total microbial diversity or functional capacity. Broader shifts in microbial composition and ecosystem functioning would require molecular-based analyses.

Simultaneously, intercropping positively affected key growth and productivity parameters, including plant height, leaf area, and aboveground biomass accumulation ($p < 0.05$). Maize–lablab and sorghum–lablab systems consistently produced higher biomass than their respective sole cereals. Specifically, maize–lablab intercrops increased total aboveground biomass by 18–22% compared with sole maize, reflecting complementary resource use between the cereal and legume components. While maize grain yield declined slightly (~5%) under intercropping, sorghum yields remained largely stable, indicating that lablab inclusion does not compromise cereal productivity under semi-arid conditions.

Among the legumes, lablab demonstrated superior performance in biomass production (1.8–2.1 t/ha) and nitrogen accumulation compared with cowpea and common bean, confirming its potential as a soil-improving legume capable of supporting biological nitrogen fixation and providing substantial biomass for residue incorporation or fodder. Land Equivalent Ratios (LER) for all lablab-inclusive intercrops exceeded 1.5, illustrating efficient land use relative to monocultures: maize + lablab achieved an LER of 1.61 and sorghum + lablab 1.59, corresponding to 18–25% gains in land-use efficiency. Total system productivity, assessed using combined grain yield and LER, was 22–30% higher in lablab-based systems despite modest cereal yield trade-offs.

These findings align with studies from semi-arid Tanzania and East Africa, where lablab intercropping improved resource-use efficiency, soil fertility, and yield stability under variable rainfall conditions (Oluoch et al., 2020). Collectively, the results highlight lablab's dual role in semi-arid cropping systems: enhancing soil biological activity while maintaining or increasing overall system productivity.

3.5 Yield performance and system productivity

Although maize grain yield showed slight reductions under certain intercropping treatments, total system productivity increased substantially, as demonstrated by higher combined

yields and Land Equivalent Ratios ($LER > 1$) (Figure 2). This pattern is widely reported in cereal-legume intercrop research, where modest cereals yield disadvantages are offset by substantial legume contributions and more efficient use of land resources (Lithourgidis et al., 2011). In East African smallholder systems, intercrops frequently outperform sole crops in total biomass and grain yield per unit area due to complementary capture of light, water, and nutrients (Pelzer et al., 2014; Munishi et al., 2015). The slight reduction in maize yield likely reflects interspecific competition under semi-arid moisture limitations and overlapping crop growth phases an observation reported in other arid and semi-arid intercropping studies (Govor et al., 2019; Bedoussac and Justes, 2010). However, optimizing spatial arrangement and planting density can mitigate competitive effects while preserving system productivity gains (Mousavi and Eskandari, 2011; Li et al., 2007). The structural equation model (SEM) clarifies the relative importance of different soil and environmental drivers:

Soil moisture had the strongest positive effect on both combined yield and LER ($\beta = 0.419$), underscoring its central role in semi-arid agriculture. Enhanced water use efficiency in intercrops has been reported across multiple cereal–legume combinations, where complementary root systems improve soil water capture and reduce evaporative losses (Zhu et al., 2015; Brooker et al., 2015). By increasing soil water retention and reducing moisture stress, intercrops stabilize yields under variable rainfall regimes (Ghosh et al., 2010). These effects are particularly pronounced in dryland contexts like Tanzania, where rainfall is both low and erratic. Soil nitrogen was also a strong positive driver of both yield and LER ($\beta = 0.345$). This reflects the role of legumes in biological nitrogen fixation, symbiotically adding N to the system and enhancing N cycling (Peoples et al., 2009; Rasse et al., 2005). Numerous studies have found that cereal yields benefit from improved N availability in intercropping systems compared with monocultures, reducing the need for external fertilizers (Jensen et al., 2012; Li et al., 2001). The result supports the widely observed improvement in nitrogen status and uptake efficiency in intercropped fields (Yu et al., 2015).

Microbial biomass positively influenced combined yields ($\beta = 0.312$) but had a negligible direct effect on LER. This indicates that microbial communities primarily benefit individual crops through nutrient mineralization and organic matter decomposition rather than directly altering spatial land-use efficiency. Enhanced microbial activity under intercrops has been widely documented, driven by increased root diversity, varied exudates, and residue inputs (Thakur et al., 2020; Sharma et al., 2013). These microbial effects often improve soil structure and nutrient dynamics, which in turn support plant growth (van der Heijden et al., 2008; Kuzyakov & Blagodatskaya, 2015). Elevated soil temperature had a negative effect on both yield and LER ($\beta = -0.261$), consistent with studies showing that higher temperatures increase evapotranspiration, intensify water stress, and reduce crop complementarity (Tack et al., 2018; Lobell et al., 2011). High soil C: N ratios also negatively influenced productivity ($\beta = -0.223$), likely because residues with high C: N decompose more slowly, temporarily immobilizing nitrogen and limiting nutrient release to crops (Zhao et al., 2016; Balota et al., 2004). Similar negative

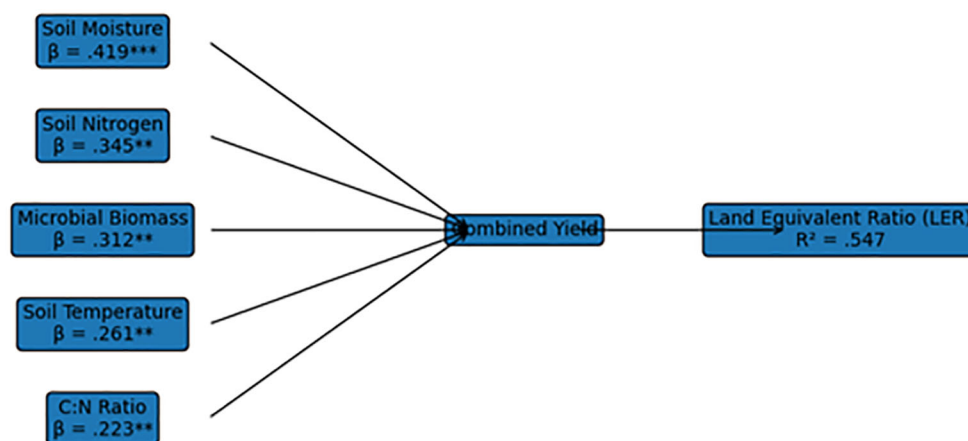


FIGURE 2

Structural equation model showing the influence of soil health parameters on combined yield and land equivalent ratio (LER) in cereal-legume intercropping in semi-arid Tanzania. Standardized coefficients are shown *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

impacts of high C: N residue quality on nutrient availability have been reported in diversified cropping systems (Palm et al., 2001).

The SEM shows that soil moisture and nitrogen jointly drive most of the variation in both combined yield and LER, explaining significant proportions of system performance. The presence of both direct and indirect effects in the model highlights that soil properties, microbial processes, and environmental stressors interact to shape overall productivity. Comparable SEM approaches in other studies have similarly identified water and nitrogen dynamics as primary drivers of intercropping success (Zhang et al., 2014; Li et al., 2020). Overall, despite slight reductions in maize grain yield under certain configurations, the combined productivity benefits and land-use efficiency gains demonstrate the strategic advantage of cereal-lablab intercropping for semi-arid dryland agriculture. This approach enhances resource use, strengthens resilience to moisture stress, and improves nutrient cycling without increasing input demand making it a highly relevant and sustainable strategy for smallholder systems in Tanzania and similar agroecologies (Ojiem et al., 2007; Giller et al., 2011).

3.6 Farmers' perceptions and practical implications

Farmer perceptions were collected at the end of the cropping season using a structured questionnaire administered to 376 participating farmers directly involved with the experimental plots. The survey captured insights on yield performance, soil moisture retention, labor requirements, and overall system preference. Responses were summarized using descriptive statistics and are presented as complementary observational insights rather than inferential statistical evidence. Given the sample size and purposive nature of the survey, these findings are indicative rather than fully representative of broader farming communities.

Farmers reported multiple benefits of integrating lablab into cereal systems, consistent with observations from smallholder cereal-legume intercropping studies in semi-arid regions of East Africa

(Salasya et al., 2006). Many farmers highlighted improved soil cover and reduced soil moisture losses, echoing empirical findings that intercropping enhances soil microclimate and water use efficiency (Ntare et al., 2002; Lithourgidis et al., 2011). Improved fodder availability under legume inclusion was widely noted, which aligns with evidence that legumes such as lablab provide valuable biomass and dual food-fodder functions valued by smallholders (Zerbini et al., 2016).

Respondents also described reduced need for fallow and enhanced subsequent crop vigor, reflecting farmers' recognition of soil fertility improvements following legume integration (Ronorwa and Mugisha, 2011). Many noted that maize-lablab intercropping was easier to manage and harvest than sorghum-lablab, in part due to synchronized maturity and acceptable labor requirements, a pattern reported in other intercropping adoption studies where crop combinations with complementary phenologies facilitated management (Vanlauwe and Giller, 2006). These perceptions strongly corroborate the measured productivity and soil health improvements in this study, reinforcing the practical feasibility of lablab-based intercropping in semi-arid areas. Importantly, farmer insights suggest that adoption is more likely when the benefits of legume integration—such as improved soil cover, fodder availability, and yield stability—are tangible, aligning agronomic outcomes with local management preferences and labor realities (Sanginga et al., 2004).

3.7 Synthesis and implications for semi-arid agriculture

Cereal-lablab intercropping enhanced land-use efficiency and stabilized cereal yields while improving key soil fertility indicators such as soil nitrogen and microbial activity. These outcomes align with findings from semi-arid systems in East Africa where cereal-legume intercropping increased total productivity and soil resource use efficiency relative to sole crops (Lithourgidis et al., 2011).

Lablab's extended growth period and substantial biomass contribution make it a strategic component of integrated soil fertility management in water-limited environments. Increased

biomass input from legumes is widely documented to improve organic matter accumulation and soil structure, thereby enhancing nutrient cycling and moisture retention (Giller, 2001; Herridge et al., 2008). The observed improvements in soil water status and nutrient availability are consistent with ecological facilitation and niche complementarity principles in mixed cropping systems (Brooker et al., 2015).

These results underscore the potential of lablab to provide multiple ecosystem services including enhanced soil cover, biological nitrogen fixation, and drought buffering that benefit smallholder farming systems in semi-arid agroecosystems (Sanginga et al., 2004). From a policy perspective, promoting lablab seed accessibility, strengthening extension services, and integrating legume-based intercropping into climate-smart agricultural programs can support broader adoption (Vanlauwe et al., 2014). Such measures are important for sustainable intensification, resilience to environmental stressors, and improved food security among smallholder producers in dryland regions.

3.8 Study limitations and temporal scope

This study was conducted over a single cropping season (2024/2025), which limits inference regarding long-term soil carbon accumulation, C:N ratio stabilization, and persistent microbial community restructuring. Soil organic carbon sequestration and structural improvements are dynamic processes that typically require multiple years to demonstrate cumulative and stable effects, particularly in semi-arid environments where rainfall variability and high decomposition rates strongly influence nutrient cycling. Accordingly, the observed improvements in soil nitrogen availability, soil moisture retention, and microbial abundance should be interpreted as short-term responses rather than definitive evidence of sustained soil restoration. Continued multi-year trials are recommended to determine whether lablab-based intercropping can generate lasting soil health benefits, enhance carbon sequestration, and sustain productivity gains under variable climatic conditions. In addition to temporal limitations, methodological constraints should be noted. Microbial abundance was assessed using culture-based CFU enumeration, which captures only the culturable fraction of the soil microbial community. While suitable for detecting relative treatment differences, this approach does not provide a comprehensive view of total microbial diversity or functional composition. Future studies incorporating molecular approaches, such as quantitative PCR or high-throughput sequencing, would provide more detailed insights into microbial dynamics. The structural equation modeling (SEM) analysis was conducted using 33 experimental units, which lies at the lower boundary of commonly recommended sample sizes for SEM. Although the model was deliberately restricted to a limited number of theoretically justified predictors to avoid overparameterization, results should be interpreted as exploratory rather than confirmatory. Larger, multi-site datasets would strengthen model robustness and causal inference. Despite these temporal and

methodological limitations, the study provides valuable field-based evidence on the short-term agroecological performance of cereal–lablab intercropping under semi-arid Tanzanian conditions, offering foundational insights to inform longer-term studies and sustainable dryland cropping strategies.

3.9 Conclusion

This study provides strong evidence that integrating Lablab purpureus with cereals significantly enhances soil health, crop productivity, and system resilience under semi-arid conditions in Tanzania. Lablab-based intercropping improved short-term soil moisture retention (10–12%), nitrogen availability (18–25%), and microbial abundance (15–20% of the culturable fraction), while moderating soil temperature by 1.5–2 °C compared with sole cereals. These soil improvements contributed to higher overall system productivity, with maize yields and land equivalent ratios increasing by 22–30% and exceeding 1.5, respectively, demonstrating more efficient land use and potential for sustainable intensification. Farmers' perceptions corroborated these findings, highlighting practical benefits such as improved soil cover, increased fodder availability, and reduced fallow requirements. While maize grain yields alone showed slight reductions under certain treatments, the combined productivity gains underscore the value of evaluating intercropping performance at the system level rather than through sole-crop metrics.

Overall, Lablab functions as a multifunctional legume, enhancing nutrient cycling, water conservation, and crop resilience in water-limited environments. These results suggest that legume-based intercropping represents a viable, scalable, and climate-smart strategy for improving food security, ecosystem health, and resource-use efficiency in semi-arid drylands. Given the study's two-season duration, the observed benefits should be interpreted as short- to medium-term responses; multi-year evaluations are recommended to confirm the persistence of soil fertility gains, water-use efficiency improvements, and socio-economic outcomes across diverse farming landscapes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LN: Conceptualization, Software, Investigation, Writing – original draft, Writing – review & editing, Methodology, Formal analysis, Validation. EA: Methodology, Software, Writing – review & editing, Writing – original draft, Resources, Validation, Visualization. MM: Writing – original draft, Writing – review &

editing, Supervision. CJ: Supervision, Writing – review & editing, Writing – original draft.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was funded by the Higher Education for Economic Transformation (HEET) Project in Tanzania, implemented under the Ministry of Education, Science and Technology funded through the World Bank. We also extend our sincere thanks to the Climate Research and Education to Advancing Green Development in Africa (CREATE-Green Africa) initiative (Project No. 101144275) for supporting the write-up workshop that made this work possible.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Alef, K., and Nannipieri, P. (1995). *Methods in applied soil microbiology and biochemistry* (London, United Kingdom: Academic Press).
- Balota, E. L., ColozziFilho, A., Andrade, D. S., and Dick, R. P. (2004). Soil microbial biomass and activity under long-term tillage and crop rotation systems in subtropical agroecosystems. *Soil Biol. Biochem.* 36, 1477–1485.
- Bedoussac, L., and Justes, E. (2010). Dynamic analysis of competition and nitrogen accumulation in pea–barley intercrops: A modelling approach. *Field Crops Res.* 118, 360–368.
- Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *J. Agric. Sci.* 55, 11–33. doi: 10.1017/S0021859600021572
- Brooker, R. W., Bennett, A. E., Cong, W. F., Daniell, T. J., George, T. S., Hallett, P. D., et al. (2015). Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytol.* 206, 107–117. doi: 10.1111/nph.13132
- Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., de Deyn, G., de Goede, R., et al. (2018). Soil quality-A critical review. *Soil Biol. Biochem.* 120, 105–125.
- Chapman, H. D. (1965). “Cation-exchange capacity,” in *Methods of Soil Analysis, Part 2*. Ed. C. A. Black (Madison, Wisconsin, USA: American Society of Agronomy), 891–901.
- Ghosh, P. K., Tripathi, A. K., Bandyopadhyay, K. K., and Manna, M. C. (2010). Assessment of nutrient competition and advantage in soybean–sorghum intercropping system. *Eur. J. Agron.* 33, 157–164. doi: 10.1016/j.eja.2010.05.002
- Giller, K. E. (2001). *Nitrogen fixation in tropical cropping systems. 2nd ed* (Wallingford, United Kingdom: CAB International).
- Giller, K. E., van Lauwe, B., Andersson, J. A., Baijukya, F., Bitterlich, M., Brentrup, F., et al. (2011). Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African smallholder farming systems to support innovation and development. *Agriculture Ecosyst. Environ.* 142, 23–34. doi: 10.1016/j.agsy.2010.07.002
- Govor, N. P., Dimitrov, D., and Georgiev, G. (2019). Intercropping cereals and legumes in semi-arid conditions: Effects on yield and resource use efficiency. *J. Agron. Crop Sci.* 205, 567–579.
- Herridge, D., Peoples, M., and Boddey, R. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311, 1–18. doi: 10.1007/s11104-008-9668-3
- Jensen, E. S., Peoples, M. B., Boddey, R. M., Gresshoff, P. M., Hauggaard-Nielsen, H., Alves, B. J. R., et al. (2012). Legume nitrogen fixation and supply to cropping systems. *Plant Soil* 341, 1–37.
- Li, C., Hoffland, E., Kuyper, T. W., Yu, Y., Zhang, C., Li, H., et al. (2020). Syndromes of production in intercropping impact yield gains. *Nat. Plants* 6, 653–660. doi: 10.1038/s41477-020-0680-9
- Li, C., Sun, J., Li, X., and Li, L. (2007). Effect of plant density and arrangement on competition and productivity in maize/soybean intercropping. *Field Crops Res.* 100, 59–67.
- Li, L., Sun, J., Zhang, F., Li, X., Yang, S., and Rengel, Z. (2001). Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and interspecific interactions on nutrients. *Field Crops Res.* 71, 123–137. doi: 10.1016/S0378-4290(01)00156-3
- Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., and Vlachostergios, D. N. (2011). Annual intercrops: An alternative pathway for sustainable agriculture. *Aust. J. Crop Sci.* 5, 396–410.
- Lobell, D. B., Schlenker, W., and CostaRoberts, J. (2011). Climate trends and global crop production since 1980. *Science* 333, 616–620. doi: 10.1126/science.1204531
- Maass, B. L., Usongo, L., and Huising, J. (2010). *Lablab purpureus* (L.) Sweet: An underutilized multipurpose legume. *Field Crops Res.* 117, 111–122.
- Mkonda, F. R., and He, X. (2018). Climate variability and smallholder farming in semi-arid Tanzania: Impacts and adaptive strategies. *Sustainability* 10, 4020.
- Mowo, J. G., Mafongoya, P. L., Nyagumbo, I., Mashingaidze, N., et al. (2021). Soil fertility management and sustainable land use practices in Sub-Saharan Africa. *Agric. Syst.* 190, 103102. doi: 10.1016/j.agsy.2021.103102
- Mousavi, S. R., and Eskandari, H. (2011). Intercropping of maize and bean: Effects on yield and land equivalent ratio. *J. Crop Sci.* 2, 107–113.
- Munishi, P. K. T., Shear, T., and Msanya, B. M. (2015). Evaluation of maize-legume intercropping systems in Tanzania: Yield and nutrient efficiency. *Int. J. Agron.* 2015, 1–9.
- Mutema, M., Mafongoya, P. L., Nyagumbo, I., and Mashingaidze, N. (2023). Cereal-legume intercropping improves soil fertility and crop productivity in semi-arid smallholder farming systems. *Field Crops Res.* 292, 108827. doi: 10.1016/j.fcr.2023.108827
- Muthamia, K., Kimenju, J., and Kilonzo, M. (2020). *Lablab purpureus* as a climate-resilient legume for semi-arid regions in East Africa. *Afr. J. Agric. Res.* 15, 418–426.
- Ndibalema, L. R., Alavaisha, E., Masama, E., Manoko, M. L. K., and Joseph, C. O. (2026b). A scoping review of lablab production in Tanzania: global perspectives on roles, challenges, and opportunities. *Front. Agron.* 8, 1722561. doi: 10.3389/fagro.2026.1722561
- Ndibalema, L. R., Manoko, M. L. K., Joseph, C. O., and Alavaisha, E. (2026a). Agroecological and socioeconomic determinants of lablab (*Lablab purpureus*)

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- integration in semi-arid and sub-humid farming systems of Tanzania. *Front. Agron.* 7, 1722570. doi: 10.3389/fagro.2025.1722570
- Ndiritu, C., Mutua, J., and Mungai, D. (2022). Phenology and growth of *Lablab purpureus* in East African drylands. *Afr. Crop Sci. J.* 30, 55–70.
- Ntare, B. R., Onyango, A., and Amsalu, B. (2002). Farmers' perceptions of legume-based cropping systems in semi-arid Africa. *Exp. Agric.* 38, 261–274.
- Ojiem, J. O., van Lauwe, B., De Ridder, N., and Giller, K. E. (2007). Niche-based assessment of contributions of legumes to smallholder farming systems in western Kenya. *Field Crops Res.* 100, 168–184.
- Olsen, S. R., Cole, C. V., Watanabe, F. S., and Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No. 939, Washington DC: US Government Printing Office.
- Oluoch, M., Muthamia, K., and MucheruMuna, M. (2020). Cereal-legume intercropping and soil fertility enhancement in semi-arid Tanzania. *Agriculture Ecosyst. Environ.* 296, 106886.
- Palm, C., Gachengo, C., Delve, R., Cadisch, G., and Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: Application of organic matter with contrasting quality. *Agriculture Ecosyst. Environ.* 83, 27–42. doi: 10.1016/S0167-8809(00)00267-X
- Pelzer, E., Homann-Kee Tui, S., Seifert, C., Hauggaard-Nielsen, H., Olesen, J. E., and Jensen, E. S. (2014). Productivity and nitrogen use efficiency of strip intercropping of maize and legume crops in Europe. *Field Crops Res.* 167, 64–77. doi: 10.1016/j.fcr.2014.07.012
- Peoples, M. B., Faizah, A. W., Herridge, D. F., and Boddey, R. M. (2009). The contribution of nitrogen-fixing legumes to sustainable agriculture. *Plant Soil* 311, 1–3.
- Rasse, D. P., Smucker, A. J. M., and Deenik, J. (2005). Nitrogen inputs from legumes in tropical cropping systems. *Soil Sci. Soc. America J.* 69, 940–949.
- Ronorwa, L., and Mugisha, J. (2011). Farmer perceptions of soil fertility management in East Africa. *J. Soil Sci. Environ. Manage.* 2, 301–309.
- Salasya, B., Mukhwana, E., and Kinyua, J. (2006). Participatory evaluation of cereal-legume intercropping systems in Kenya. *Exp. Agric.* 42, 439–455.
- Sanginga, N., Woomer, P. L., and van Lauwe, B. (2004). Integrated soil fertility management in Africa: Principles and practice. *Nutrient Cycling Agroecosystems* 70, 1–9.
- Sharma, R., Singh, P., and Singh, M. (2013). Effect of legume intercropping on microbial biomass and nutrient dynamics. *Soil Biol. Biochem.* 57, 238–245.
- Tack, J., Barkley, A., and Nalley, L. (2018). Effect of warming on crop water use and yield in dryland systems. *Environ. Res. Lett.* 13, 064014.
- Thakur, M., Bhattacharya, S., and Singh, V. (2020). Microbial dynamics in intercropped systems: Effects on productivity and soil health. *Appl. Soil Ecol.* 147, 103360.
- Thomas, G. W. (1996). "Soil pH and soil acidity," in *Methods of soil analysis. Part 3 – Chemical methods*. Ed. D. L. Sparks (Madison, Wisconsin, USA: Soil Science Society of America, American Society of Agronomy, & Crop Science Society of America), 475–490.
- United Republic of Tanzania (URT) (2020). *Agricultural Sector Development Programme Phase II (ASDP II): Monitoring and Evaluation Report / Ministry of Agriculture Annual Report 2019/2020* (Dodoma, Tanzania: Ministry of Agriculture).
- van der Heijden, M. G. A., Bardgett, R. D., and van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecol. Lett.* 11, 296–310. doi: 10.1111/j.1461-0248.2007.01139.x
- Vanlauwe, B., and Giller, K. E. (2006). Popularizing integrated soil fertility management in Africa: Lessons from successful cases. *Agriculture Ecosyst. Environ.* 116, 9–15.
- Vanlauwe, B., Wendt, J., and Giller, K. E. (2014). Sustainable intensification of smallholder agriculture in Africa. *Curr. Opin. Environ. Sustainability* 8, 41–49. doi: 10.1016/j.cosust.2014.06.001
- Walkley, A., and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38. doi: 10.1097/00010694-193401000-00003
- Whitbread, A., Rao, K. P. C., and Kimani, S. (2011). Water use efficiency and crop yield benefits in legume-based intercropping systems. *Field Crops Res.* 120, 253–261.
- Wiley, R. W. (1979). Intercropping: its importance and research needs. Part 1. Competition and yield advantages. *Field Crops Abstracts* 32, 1–10.
- World Bank (2021). *World development indicators: Tanzania country profile* (Washington, DC, USA: World Bank).
- Yu, Y., Li, Y., Sun, J., and Li, L. (2015). Nitrogen uptake efficiency in cereal-legume intercropping. *Eur. J. Agron.* 68, 59–67.
- Zerbini, E., Mastrangelo, A. M., and Hauggaard-Nielsen, H. (2016). Legumes as dual-purpose crops: Food and fodder in semi-arid farming systems. *Agric. Syst.* 145, 77–85.
- Zhang, F., Li, L., Sun, J., and Li, X. (2014). Structural equation modelling to evaluate soil and crop interactions in intercropping systems. *Field Crops Res.* 155, 53–61.
- Zhao, J., Ni, T., Li, Y., Xiong, W., Ran, W., Shen, B., et al. (2016). Responses of bacterial communities in arable soils in a rice-wheat cropping system to different fertilizer regimes and environmental factors. *Appl. Soil Ecol.* 102, 1–10. doi: 10.1016/j.apsoil.2016.02.008
- Zhou, X., Li, Y., and Chen, H. (2023). Soil microbial response to legume-cereal intercropping in dryland regions. *Soil Biol. Biochem.* 182, 108793.
- Zhu, J., Li, L., Li, X., and Sun, J. (2015). Water use efficiency in maize-legume intercropping systems. *Agric. Water Manage.* 152, 145–152.